

# Search for Particles and Forces Beyond the Standard Model at HERA $ep$ and Tevatron $p\bar{p}$ Colliders\*

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## Abstract

A review of searches for physics beyond the Standard Model carried out at high energy lepton-hadron and hadron-hadron facilities is presented, with emphasis on topics of interest for future data taking at the upgraded Tevatron  $p\bar{p}$  and HERA  $ep$  colliders. The status and discovery prospects are discussed for leptoquarks, Technicolour and supersymmetry, forbidden lepton and quark flavour-changing processes, extra gauge bosons, excited states of composite fermions, generic contact interactions and extra compactified dimensions.

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# 1 Introduction

Although remarkably confirmed at the phenomenological level over the past quarter of century, in particular most recently at high-energy colliders, the Standard  $SU(3) \times SU(2) \times U(1)$  Model of strong, electromagnetic and weak forces remains incomplete and unsatisfactory. There are reasons to believe that the search for new physics could be fruitful at existing colliders in the years to come, hopefully providing a deeper understanding of elementary forces in Nature.

The Standard Model is incomplete and unsatisfactory because, first of all, it only offers a partial “unification” of the electroweak and strong forces. Quarks are assumed to carry flavour degrees of freedom and colour quantum numbers somehow independently. The electroweak interactions couple only to flavours and are indifferent to colours. The strong interaction of coloured quarks and gluons described by the  $SU(3)$  quantum chromodynamics (QCD) gauge field theory remains separate. A “Grand Unification” of carriers of fundamental interactions in, for instance, a larger local gauge theory is simply postponed. Needless to say, no connection is made at an even grander level with an eventual quantum theory of gravity.

The Standard Model’s predictive power moreover suffers from a large number of arbitrary parameters. For instance, the particle masses are not predicted and must be measured experimentally. These masses are assumed to originate solely from the electroweak sector. A fundamental scalar field, the Higgs-boson field, is assumed to pervade the universe and to possess, through self-interaction, a non-zero field strength of  $v = (\sqrt{2}G_F)^{-1/2} \simeq 246$  GeV of the ground state. This non-zero vacuum expectation value induces a breaking of the electroweak  $SU(2)_L \times U(1)_Y$  symmetry down to the electromagnetic  $U(1)_{EM}$  symmetry. This “Higgs mechanism”, which gives masses to the  $W^\pm$  and  $Z$  bosons and leaves the photon massless, remains unproven. The mass of the Higgs boson itself is not predicted by the Standard Model but an upper bound must nevertheless be imposed to preserve the internal consistency of the model. It is the Yukawa interactions, of arbitrary strengths, of fermions with the Higgs field that are assumed to be responsible for the fermion masses after electroweak symmetry breaking. In contrast, the local gauge symmetries of the strong interactions remain unbroken at all levels of the theory. The masses of protons and neutrons, which themselves contribute to more than 99% of the mass of ordinary cold matter, are understood to originate from the dynamics of colour confinement in QCD.

In the Standard Model there are no direct couplings between quark and lepton families and the theory is consistent with a separate and exact conservation of lepton and baryon numbers in all processes. The viability of the Standard Model rests on a somewhat empirical similarity between lepton and quark sectors. Disastrous anomalies that would prevent renormalizability of the theory are avoided by an exact cancellation between contributions of lepton and quark fields. No deeper understanding is provided for this exact cancellation, which happens thanks to the special arrangement of fermion multiplets in the model and the fact that quarks have the additional colour degree of freedom. At a more fundamental level, the structure of the leptonic and quarkonic sectors could, for instance, imply the existence of new bosonic carriers of lepton and baryon numbers.

Finally, the Standard Model incorporates an apparent threefold “replica” of fermion generations which remain unexplained. The electroweak interaction Lagrangian is simply constructed separately for each of the lepton and quark generations, with anomalies cancelled within each generation. There are no direct couplings between different lepton families while, intriguingly, three quark families (at least) are needed if quark mixing is to be the cause of all observed electroweak CP violation. The existence of the fermion generations could be hinting that more elementary constituents exist which

Table 1: Main contemporary collider facilities. These are listed together with their beam particles and the available centre-of-mass energies. Also given are the integrated luminosities accumulated (or expected) per experiment. The multiplicative factor after the  $\otimes$  sign denotes the number of multi-purpose collider experiments operating simultaneously at each of the facilities.

Collider	Beams	$\sqrt{s}$	$\int \mathcal{L} dt$	Years
LEP <sub>I</sub>	$e^+e^-$	$M_Z$	$\sim 160 \text{ pb}^{-1} \otimes 4$	1989-95
LEP <sub>II</sub>	$e^+e^-$	$> 2 \times M_W$	$\sim 620 \text{ pb}^{-1} \otimes 4$	1996-00
HERA <sub>Ia</sub>	$e^-p$	300 GeV	$\mathcal{O}(1 \text{ pb}^{-1}) \otimes 2$	1992-93
HERA <sub>Ib</sub>	$e^\pm p$	$\lesssim 320 \text{ GeV}$	$\mathcal{O}(100 \text{ pb}^{-1}) \otimes 2$	1994-00
Tevatron <sub>Ia</sub>	$p\bar{p}$	1.8 TeV	$\mathcal{O}(10 \text{ pb}^{-1})$	1987-89
Tevatron <sub>Ib</sub>	$p\bar{p}$	1.8 TeV	$\mathcal{O}(100 \text{ pb}^{-1}) \otimes 2$	1992-96
HERA <sub>II</sub>	$e_{L,R}^\pm p$	$\sim 320 \text{ GeV}$	$\sim 1 \text{ fb}^{-1} \otimes 2$	2002-06
Tevatron <sub>IIa</sub>	$p\bar{p}$	$\sim 2.0 \text{ TeV}$	$\sim 2 \text{ fb}^{-1} \otimes 2$	2002-05
Tevatron <sub>IIb</sub>	$p\bar{p}$	$\sim 2.0 \text{ TeV}$	$\mathcal{O}(10 \text{ fb}^{-1}) \otimes 2$	2005-08

form the known quarks and leptons.

The dissatisfaction with the Standard Model makes the search for new physics a central duty in experiments at colliders. Existing or planned lepton-hadron and hadronic colliders could provide the required discovery reach. This is motivated on the theoretical side, where there exists in various more-or-less predictive models a strong prejudice for new physics “close to” electroweak unification scale. For example, supersymmetric models like the Minimal Supersymmetric Standard Model or minimal Supergravity would most naturally yield a rich phenomenology at the  $\mathcal{O}(\text{TeV})$  scale. This is because the mass difference between ordinary particles and their supersymmetric partners must not be too large if such models are to be useful to avoid excessive “fine tuning” while preserving the masses in the Higgs scalar sector from quadratically divergent renormalization corrections. Another example is provided by theories which attempt to unify all known interactions including gravity. It has been realized recently that a relevant scale for quantum-gravity models with “large” compactified extra dimensions could be as low as  $\mathcal{O}(1 \text{ to } 10 \text{ TeV})$  with possibly observable effects at colliders from the propagation of fields in the extra dimensions. Technicolour models in which new composite scalar fields are responsible for the electroweak symmetry breaking possibly also yield a rich spectrum of new composite states accessible at colliders. On the experimental side, the recent observation of neutrino oscillations [1] could be a guiding sign towards physics beyond the Standard Model. In the forthcoming years, scales from 1 to 10 TeV will be best probed in complementary facilities such as the HERA  $ep$  and the Tevatron  $p\bar{p}$  upgraded colliders (Table 1).

These  $ep$  and  $p\bar{p}$  colliders are well suited to search for new physics affecting lepton-quark couplings. For  $ep$  colliders this is obvious given the quantum numbers available in the initial state, which allow for contributions to the process  $eq \rightarrow eq$  via  $s$ -channel resonant production or  $u$ -channel virtual exchange of new bosons coupling to lepton-quark pairs. In  $p\bar{p}$  collisions, such new bosons, if pair produced, could be easily recognized via their decay, possibly leading to final states involving lepton pairs. Furthermore, the  $t$ -channel exchange of such a boson could contribute to the Drell-Yan-like process  $q\bar{q} \rightarrow l\bar{l}$ . The status of the searches for leptoquark production will be discussed in section 2. Searches motivated by

theories possessing new composite or elementary scalar fields are then discussed in section 3. We review collider constraints on Technicolour models, which are models designed to provide an alternative to the Higgs mechanism in the Standard Model and which contain leptoquark-like particles.

The phenomenology and searches for supersymmetric (SUSY) particles are discussed in section 4, with some emphasis on  $R$ -parity-violating theories. New Yukawa couplings to lepton-quark pairs appear in such theories where they connect the SUSY scalar partners of known fermions to ordinary matter via lepton-number violating interactions. In view of existing indirect constraints, the collider facilities appear particularly competitive for couplings involving heavy quark flavours. Particular attention is given to searches and constraints on stop squarks. New bosons couplings to lepton-quark pairs are one of the various possible contributions beyond the Standard Model to flavour-changing neutral currents. The sensitivity of collider experiments to such currents is compared in the top sector using an effective Lagrangian approach in section 5. The search for lepton-flavour-violation processes in an effective and generic approach is also discussed in this section 5.

Searches for new vector gauge bosons or new scalar Higgs bosons predicted by theories incorporating an extension of the electroweak gauge symmetries are discussed in section 6.

Direct searches for excited fermions are discussed in section 7. A comparison of the sensitivity of existing colliders to contact interactions is presented in section 8 in the context of compositeness and leptoquark models. The possible effects on inclusive measurements of the exchange of gravitons which are allowed to propagate in the extra compactified dimensions in  $(4 + n)$ -dimensional string theory are discussed in section 9.

A summary and conclusions on future discovery prospects are presented in section 10.

## 2 Leptoquarks

### 2.1 Introduction

An intriguing property of the Standard Model is the apparent symmetry between the lepton and quark sectors. This symmetry is manifest in their assignment to singlets and doublets of the weak interaction, with their “replica” over three fermion generations. This symmetry is furthermore essential in achieving an exact cancellation of chiral (triangular) anomalies. The cancellation demands that the sum of the electric charges is exactly neutralized in each generation, which incidentally requires three quark colours. This could possibly be an indication that leptons and quarks are fundamentally connected through a new “lepto-quark” interaction.

Leptoquarks (LQs) are colour-triplet scalar (S) or vector (V) bosons carrying lepton and baryon numbers, and a fractional electromagnetic charge,  $Q_{em}$ . They appear naturally in Grand Unified Theories (GUT) for electroweak and strong interactions of both the “Georgi-Glashow type” [2] (based on simple gauge groups with a superheavy unifying mass scale) or of the “Pati-Salam type” [3] (with flavour-colour and left-right symmetric semi-simple gauge groups with intermediate or low unifying mass scale), as well as in superstring-“inspired”  $E_6$  models [4]. They also appear as mediators between quark and lepton doublets in horizontal-symmetry schemes [5], in Technicolour theories addressing the issue of electroweak symmetry breaking (see section 3.1), in strongly coupled weak-interaction models attempting to reconcile the conceptual differences between the weak and strong sectors [6], and in some matter-compositeness theories [7] attempting to provide an explanation for the three generations of fermions. Actual searches at colliders have been mostly carried out in the context of effective models.

### 2.2 Effective Interactions, Models and Nomenclature

A most general effective Lagrangian for leptoquark interactions with SM fermion pairs was proposed by Buchmüller, Rückl and Wyler [8] under the assumptions that leptoquarks: **i)** have renormalizable interactions; **ii)** have interactions invariant under Standard Model  $SU(3) \times SU(2) \times U(1)$  gauge groups; **iii)** couple only to Standard Model fermions and gauge bosons. Furthermore, unacceptable instability of the proton is avoided by imposing that leptoquarks: **iv)** conserve leptonic number  $L_l$  and baryonic number  $B_q$  separately. Such leptoquarks carry a fermionic number  $F = 3B_q + L_l$  of either  $|F| = 0$  or 2 and have interactions with lepton-quark pairs described by [8]

$$\mathcal{L} = \mathcal{L}_{|F|=2} + \mathcal{L}_{F=0}$$

with

$$\begin{aligned} \mathcal{L}_{|F|=2} &= (g_{1L}\bar{q}_L^c i\tau_2 l_L + g_{1R}\bar{u}_L^c e_R^-)S_0 + \tilde{g}_{1R}\bar{d}_R^c e_R^- \tilde{S}_0 + g_{3L}\bar{q}_L^c i\tau_2 \tau l_L S_1 \\ &\quad + (g_{2L}\bar{d}_R^c \gamma^\mu l_L + g_{2R}\bar{q}_L^c \gamma^\mu e_R^-)V_{1/2\mu} + \tilde{g}_{2L}\bar{u}_R^c \gamma^\mu l_L \tilde{V}_{1/2\mu} + h.c. \\ \mathcal{L}_{F=0} &= (h_{1L}\bar{q}_L \gamma^\mu l_L + h_{1R}\bar{d}_R \gamma^\mu e_R^-)V_{0\mu} + \tilde{h}_{1R}\bar{u}_R \gamma^\mu e_R^- \tilde{V}_{0\mu} + h_{3L}\bar{q}_L \tau \gamma^\mu l_L V_{1\mu} \\ &\quad + (h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R^-)S_{1/2} + \tilde{h}_{2L}\bar{d}_R l_L \tilde{S}_{1/2} + h.c., \end{aligned}$$

where  $q_L$  and  $l_L$  are the  $SU(2)_L$  left-handed quark and lepton doublets and  $e_R, d_R$  and  $u_R$  denote the corresponding right-handed singlets for leptons,  $d$ -type and  $u$ -type quarks. The  $\psi^c$  are the charge conjugate of the fermion fields with the convention  $\psi^c \equiv C\bar{\psi}^T$ . The indices  $L$  and  $R$  appended to the

coupling constants correspond to the chirality of the lepton involved. For simplicity, the colour and generational indices have been suppressed.

Having chosen for the leptoquark interactions with lepton-quark pairs the above effective Lagrangian which preserves the symmetries of the Standard Model, the possible representations of the leptoquarks with respect to the gauge groups and the couplings to the gauge bosons are in principle completely determined. This is strictly true for scalars. However, for vector leptoquarks interacting with gauge bosons ( $g$ ), the cross-section that depends on trilinear  $gVV$  and quartic  $ggVV$  couplings might require damping by the introduction of anomalous couplings. These will be necessary for instance if the vector leptoquarks are composite low-energy manifestations of a more fundamental theory at higher energy scales. Four independent anomalous couplings  $\kappa_\gamma$ ,  $\kappa_Z$ ,  $\lambda_\gamma$  and  $\lambda_Z$  are introduced for the electroweak sector. A theory with pure Yang-Mills couplings is recovered by setting  $\kappa_{\gamma,Z} = \lambda_{\gamma,Z} = 0$ . Models with “minimal vector couplings” are obtained by setting  $\kappa_{\gamma,Z} = 1$  and  $\lambda_{\gamma,Z} = 0$ . A discussion of the leptoquark interactions with  $\gamma$  and  $Z$  bosons in a model-independent effective Lagrangian approach can be found in Refs. [9, 10]. Two anomalous couplings  $\kappa_g$  and  $\lambda_g$  are introduced for the strong sector. A general effective Lagrangian for the interactions with gluons can be found in Ref. [11].

Two further restrictions can be imposed to cope with the existing low-energy constraints [12, 13] in what will be henceforward called the “minimal Buchmüller-Rückl-Wyler effective model” (mBRW). In the mBRW model, leptoquarks: **v**) each couple to a single lepton-quark generation  $i$  with  $i = 1, 2$  or  $3$ ; **vi**) each has pure chiral couplings to SM fermions. With the restrictions imposed to the mBRW model, it will be sufficient to use the generic symbol  $\lambda$  for the different Yukawa couplings  $g, \tilde{g}, h$  and  $\tilde{h}$ . The restriction  $\lambda^i \times \lambda^j \simeq 0$  ( $i \neq j$ ) on inter-generational connections avoids possibly large tree-level flavour-changing neutral currents and flavour-universality violations. The last restriction  $\lambda_L \times \lambda_R \simeq 0$  avoids direct contributions to chirally suppressed meson decays such as the process  $\pi \rightarrow e\nu$  as well as for instance virtual-loop contributions to the  $g - 2$  of the muon.

For each fermion generation  $i$ , the mBRW model allows for the existence of five different weak-isospin families (iso-singlets, iso-doublets and iso-triplets) for both scalar and vector leptoquarks. These are listed in Table 2.

For experimental searches, mass degeneracy is generally assumed within each isospin family. This is motivated theoretically since one would expect all leptoquarks within a given  $SU(2)_L$  representation to be degenerate apart from loop corrections. Hence, for simplicity, the same symbol represents any of the various states of different electric charges within a family. For instance, the  $S_{1/2,L}$  designates both the scalar leptoquark  $S_{1/2}$  states of electric charge  $-5/3$  and  $-2/3$  coupling to a left-handed lepton. In total, one distinguishes fourteen types of leptoquarks; seven scalars with either  $|F| = 2$  ( $S_{0,L}$ ,  $S_{0,R}$ ,  $\tilde{S}_{0,R}$ ,  $S_{1,L}$ ) or  $F = 0$  ( $S_{1/2,L}$ ,  $S_{1/2,R}$ ,  $\tilde{S}_{1/2,L}$ ), and seven vectors with either  $|F| = 2$  ( $V_{1/2,L}$ ,  $V_{1/2,R}$ ,  $\tilde{V}_{1/2,L}$ ) or  $F = 0$  ( $V_{0,L}$ ,  $V_{0,R}$ ,  $\tilde{V}_{0,R}$ ,  $V_{1,L}$ ). By construction, the decay branching ratios  $\beta(LQ \rightarrow lq)$  of each of these leptoquarks into a final state with a charged lepton  $l$  are fixed by the model to 0,  $1/2$  or 1.

Generally, only a subset of the allowed BRW-leptoquark states are predicted by a specific fundamental model. For instance, the scalar leptoquark corresponding to the  $S_{0,L}$  of Table 2 is the one present in superstring-inspired  $E_6$  theories [4]. A light scalar iso-doublet of leptoquarks corresponding to the anti- $\tilde{S}_{1/2}$  of Table 2 has been proposed [15] in a model that attempts to reconcile  $SU(5)$  GUT theories with the existing constraint on the proton lifetime and the observed  $\sin^2 \theta_W$ . Light colour-exotic scalars appear to be a generic feature in such models [16]. In contrast, a weak-isospin singlet vector leptoquark of hypercharge  $2/3$  and corresponding to the  $V_0$  appears in the Pati-Salam GUT model [3]. Interestingly, all possible fourteen states appear in a GUT theory based on the  $SU(15)$  gauge group [17, 18].

Enriched phenomenology appears in leptoquark models that depart from the assumptions of the BRW model [19]. Instead of relying on a specific model, searches at colliders can be performed in what will be henceforward called “generic models”; models in which  $\beta(LQ \rightarrow lq)$  is simply left as a free parameter. This is assumed to be made possible by (e.g.) dropping some of the above constraints. It might be for instance reasonable to assume, contrary to assumption (iii), that leptoquarks also couple to other (unspecified) new fields. Alternatively, relaxing the assumptions (iv) or (v) in the lepton sector could open new lepton-flavour violating (LFV) decays. The low-energy constraints and the discovery reach at colliders in this particular case will be discussed in section 5. Squarks in  $R$ -parity violating supersymmetry (see section 4) can fall, from a phenomenological point of view, into the “free  $\beta$ ” category of the “LQ” phenomenology. This is because they might possess leptoquark-like decay modes through Yukawa couplings in addition to their normal decay modes through gauge couplings. The  $\tilde{u}$ -like and  $\tilde{d}$ -like squarks can have lepton-quark couplings resembling those of the  $\tilde{S}_{1/2}$  and  $S_0$  leptoquarks, respectively. For instance, the  $\tilde{u}_L$  (the superpartner of the left-handed  $u$  quark) may couple to an  $e^+ + d$  pair via a Yukawa coupling  $\lambda'_{111}$  in a way similar to the coupling of the first generation  $\tilde{S}_{1/2,L}$  leptoquark of charge  $|Q_{em}| = 2/3$ . Via the same coupling, the  $\tilde{d}_R$  (the superpartner of the right-handed  $d$  quark) couples to  $e^- + u$  or  $\nu_e + d$  pairs like the first-generation  $S_{0,L}$  of charge  $|Q_{em}| = 1/3$ . As a general consequence, it will be possible to translate constraints on the  $\lambda$  couplings of leptoquarks into constraints on the  $\lambda'_{ijk}$  couplings of squarks in  $R$ -parity violating supersymmetry. However, as will be discussed in section 4, additional constraints will affect the  $\lambda'_{ijk}$  couplings since they also induce decays of other supersymmetric particles and, in contrast to LQ couplings, enter into explicit lepton-number violating processes.

## 2.3 Phenomenology at Colliders

Diagrams for the production or exchange of leptoquarks at  $e^+e^-$ ,  $p\bar{p}$  and  $ep$  colliders are shown in Fig. 1.

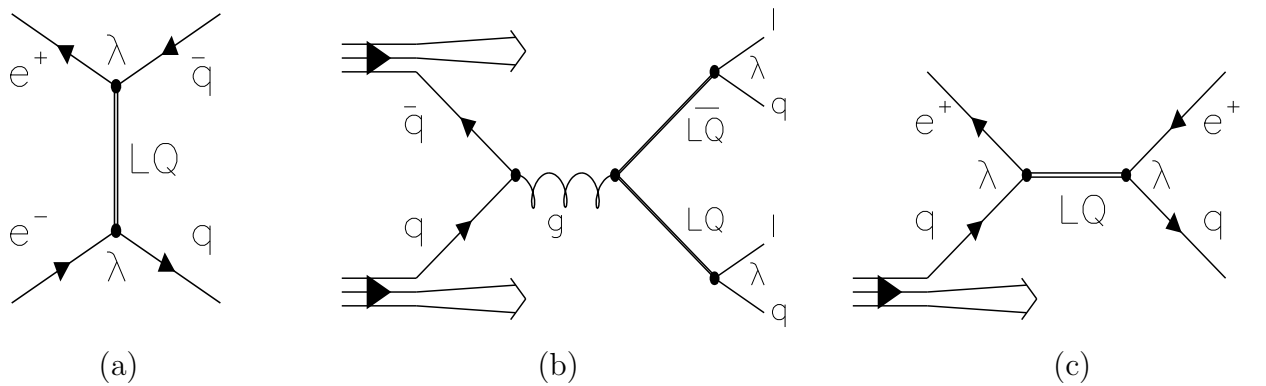


Figure 1: Typical diagrams for leptoquark production at colliders; a)  $t$ -channel exchange in  $e^+e^- \rightarrow q\bar{q}$ ; b) pair-production in  $p\bar{p} \rightarrow LQ\bar{L}\bar{Q} + X \rightarrow \ell\bar{\ell}q\bar{q} + X$ ; c)  $s$ -channel resonance in  $ep \rightarrow LQ + X \rightarrow eq + X$ .



### 2.3.1 Leptoquarks at $e^+e^-$ Colliders

Leptoquarks of all three generations can be pair-produced at an  $e^+e^-$  collider through  $s$ -channel  $\gamma$  and  $Z^0$  exchange, and in addition, leptoquarks of the first generation can be pair-produced through  $t$ -channel quark exchange. Furthermore, they can be exchanged virtually in  $t$ -channel to contribute to the process  $e^+e^- \rightarrow q\bar{q}$ , as shown in Fig. 1(a). Single real production of leptoquarks is only possible via higher order processes, with a main contribution coming from the fusion of an incoming  $e$  beam particle with a  $q$  from the resolved component of a (quasi-real)  $\gamma^*$  radiated off the other  $e$  beam [20]. However, the sensitivity of LEP<sub>II</sub> for leptoquarks in this production mode is smaller than that of HERA.

Detailed expressions of the total and differential cross-sections for leptoquark production at  $e^+e^-$  colliders can be found in [9]. The total pair-production cross-sections for the various leptoquark species strongly depend on their specific  $SU(2)_L \times U(1)_Y$  quantum numbers. For collider centre-of-mass energies  $\sqrt{s_{ee}} \gg M_Z$  and a leptoquark mass  $M_{LQ} \lesssim 1/2 \times \sqrt{s_{ee}}$ , they can vary by an order of magnitude among scalar or vector species and are systematically larger for vectors. The largest cross-sections for vector leptoquarks are expected for a ‘‘Yang-Mills’’ model (i.e.  $\kappa_{\gamma,Z} = \lambda_{\gamma,Z} = 0$ , see section 2.2). In contrast, the set of anomalous-coupling values that minimizes the total cross-section (‘‘Minimal  $\sigma_{LQ}$  scenario’’), thus leading to most conservative constraints, depends [10] on the kinematic factor  $\beta = \sqrt{1 - 4M_{LQ}^2/s_{ee}}$ . It does not in general coincide with the ‘‘Minimal vector couplings’’ scenario (i.e.  $\kappa_{\gamma,Z} = 1$  and  $\lambda_{\gamma,Z} = 0$ ).

The  $t$ -channel quark exchange contributes significantly to leptoquark pair production only if the Yukawa interaction is of electromagnetic strength (i.e. if  $\lambda$  approaches  $\sqrt{4\pi\alpha}$ ). It interferes with the  $s$ -channel pair production.

Pair-produced scalar and vector leptoquarks can be distinguished by their angular distributions  $(1/\sigma)d\sigma/d\cos\theta$ , where  $\theta$  is the polar angle of the leptoquark relative to the incident electron. In the  $s$ -channel, scalar leptoquarks are produced with an approximate  $\sin^2\theta$  distribution while vector leptoquarks are produced approximately flat in  $\cos\theta$ .

The virtual  $t$ -channel exchange of leptoquarks can be detected by a  $q\bar{q}$  production cross-section departing from Standard Model expectation and in jet-charge asymmetry measurements. Since it is a virtual exchange, the analysis in this channel is sensitive to leptoquark masses much higher than  $\sqrt{s_{ee}}$ . More detailed discussions in this ‘‘contact interaction’’-type analysis appear in section 8.

### 2.3.2 Leptoquarks at $p\bar{p}$ and $pp$ Colliders

The dominant production processes for leptoquarks at hadronic machines such as the Tevatron  $p\bar{p}$  collider are pair-production via gauge couplings in  $q\bar{q}$  annihilation and  $gg$  fusion. Leptoquarks of all three generations can be thus produced. An example diagram is shown in Fig. 1(b). In addition, leptoquarks of the first generation can be exchanged singly in  $t$ -channel virtual processes.

For scalar leptoquarks, the total pair-production cross-section is essentially parameter free. For vector leptoquarks, additional anomalous-coupling parameters  $\kappa_g$  and  $\lambda_g$  are introduced (see section 2.2) and treated as independent<sup>1</sup>. The production cross-section is generally larger for vector leptoquarks but can vary by one or two orders of magnitude depending on the specific choices of anomalous-coupling values [11, 13]. The relative contributions of the  $q\bar{q}$  and  $gg$  partonic processes depends on the fraction  $\xi$  of the  $pp$  or  $p\bar{p}$  centre-of-mass energy ( $\sqrt{s_{pp}}$ ) required in the partonic subprocess, with  $gg$  always

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<sup>1</sup>As discussed in [11], the coupling parameters  $\kappa_g$  and  $\lambda_g$  can be related through the anomalous ‘magnetic’ moment and ‘electric’ quadrupole moment of the vector leptoquark in the colour field.

dominating at small  $\xi$  values and  $q\bar{q}$  dominating at  $p\bar{p}$  colliders for large enough  $\xi$  values (e.g. above  $\xi \sim 10^{-2}$ ).

Depending on whether each of the leptoquarks decays to a charged lepton or a neutrino, the final state either consists of a lepton pair and two jets ( $lljj$ ), one lepton, missing momentum and two jets ( $l\nu jj$ ) or missing momentum and two jets ( $\nu\nu jj$ ), each of which requires a different background-reduction strategy. Also, specific analysis strategies are taken depending on the generation of the leptoquarks.

In contrast to the case at  $e^+e^-$  colliders, pair-produced scalar and vector leptoquarks at hadronic colliders cannot be distinguished by their angular distributions, given only the very slight spin-related differences expected [11, 13].

The virtual  $t$ -channel exchange of leptoquarks is investigated by searching for deviations from Standard Model expectations for Drell-Yan  $e^+e^-$  production and is sensitive to leptoquark masses well above  $\sqrt{s_{pp}}$ . Results from this type of analysis will be discussed in the context of “contact interactions” in section 8.

### 2.3.3 Leptoquarks at $ep$ Colliders

First-generation leptoquarks can be resonantly produced at the HERA  $ep$  collider by the fusion of an  $e$  beam particle with a  $q$  from the proton, or exchanged in the  $u$ -channel. An example diagram is shown in Fig. 1(c). Since valence quarks dominate the parton distribution function (PDF) at the large Bjorken- $x$  values needed to produce high-mass leptoquarks,  $e^+p$  collision is most sensitive to  $F = 0$  leptoquarks and  $e^-p$  for  $|F| = 2$  leptoquarks.

The leptoquark processes interfere with  $t$ -channel electroweak-boson exchange. Thus, LQ searches at HERA involve the analysis of event signatures indistinguishable from Standard Model deep inelastic scattering (DIS) at high squared momentum transfer,  $Q^2$ . However, different angular distributions (or  $y$  distributions,  $y = Q^2/xs_{ep}$ ) can be used to separate the signal from background. The  $y$  variable (inelasticity) is related to the decay angle  $\theta^*$  in the leptoquark rest frame by  $\cos\theta^* = 1 - 2y$  in the quark-parton model. While the neutral current DIS shows a  $1/y^2$  fall-off at fixed  $x$ , scalar leptoquarks show flat  $y$  distributions and vector leptoquarks have a  $(1 - y)^2$  dependence, which is more enhanced than the SM background at large  $y$ .

For small enough Yukawa couplings ( $\lambda \ll 1$ ) and leptoquark masses not too close to the kinematical limit, the narrow-width approximation for the dominant  $s$ -channel resonance gives a good description of the production cross-section:

$$\sigma_{LQ} = \frac{\pi}{4s_{ep}} \lambda^2 \cdot q(x = \frac{M_{LQ}^2}{s_{ep}}, Q^2 = M_{LQ}^2),$$

where  $q(x, Q^2)$  is the PDF evaluated at the resonance pole for the quark flavour corresponding to the  $SU(2)$  multiplet member in Table 2. When the leptoquark mass approaches the kinematical limit and  $\lambda$  becomes large, the effect of interference with the SM diagram (photon and  $Z$  exchange) and the  $u$ -channel diagram becomes non-negligible and this simple  $\lambda^2$  dependence of the cross-section no longer holds.

The experimental search is made by looking for a mass resonance in the electron-jet final state at large  $y$ . Also a resonance search in the neutrino-jet system is possible, with the assumption that only one neutrino escapes detection and accounts for the missing momentum. In this case, the dominant SM background is charged current DIS. HERA experiments are also able to detect such leptoquark

signals with high efficiency and small background, in contrast to the  $\nu\nu jj$  analyses at Tevatron whose sensitivity becomes degraded compared to the  $eejj$  channel because of the harsh QCD background.

## 2.4 Search Results and Prospects

Early searches in ALEPH, DELPHI, L3 and OPAL experiments at LEP<sub>I</sub> concentrated on pair production in  $Z^0$  decays [21]. Leptoquarks of all types and of each generation were considered. Direct searches for singly and pair-produced LQ as well as indirect searches from virtual exchange have been recently performed [22] at LEP<sub>II</sub>. Early searches for pair production of scalar and vector leptoquarks of all three generations have been carried out by the CDF and DØ experiments [23] and recently updated [24, 25, 26, 27, 28, 29, 30, 31] to consider all available data from Tevatron<sub>I</sub>. Searches by the H1 and ZEUS experiments using early  $e^-p$  data from 1993-94 were discussed in Refs. [32]. Results based on  $e^+p$  data up to 1997 were discussed in Refs. [33, 34, 35].

Recent H1 and ZEUS results combining most or all available  $e^\pm p$  HERA<sub>I</sub> data taken from 1994 to 2000 are discussed in Refs. [36, 37, 38, 39]. The exclusion limits thus obtained by ZEUS for first-generation leptoquarks in the framework of the BRW model are shown for all leptoquark types in Fig. 2.

The sensitivities of the collider searches for first-generation leptoquarks of the BRW model are compared in Fig. 3 for a typical scalar with  $F = 0$ , namely the  $\tilde{S}_{1/2,L}$  for which  $\beta_{eq} \equiv \beta(LQ \rightarrow e^+q) = 1.0$ . The Tevatron<sub>I</sub> experiments exclude leptoquark masses up to 242 GeV independently of  $\lambda$  for a scalar carrying the quantum numbers of this  $\tilde{S}_{1/2,L}$ . For a  $S_{0,L}$  ( $\beta = 0.5$ ), the exclusion limit decreases to 204 GeV. For an interaction stronger than the electromagnetic interaction (i.e.  $\lambda^2/4\pi\alpha > 1$ ), virtual LQ exchange at HERA<sub>I</sub> and LEP<sub>II</sub> provide comparable exclusion limits. For smaller values of  $\lambda$ , in the mass range beyond the reach of Tevatron<sub>I</sub> and below  $\sim 300$  GeV, a discovery domain remains open for HERA<sub>II</sub>. This domain will be ultimately covered independently of  $\lambda$  at Tevatron<sub>II</sub>.

The allowed domain for a possible discovery of leptoquarks at colliders is furthermore restricted by severe and utterly unavoidable constraints from low-energy experiments. These indirect constraints for leptoquarks of the mBRW model have been studied in detail in Refs [12, 19, 41]. The most stringent bounds originate from measurements of Atomic Parity Violation and from the universality in leptonic  $\pi$  decays. Lower limits in the TeV range on the ratio  $M/\lambda$  are found for all leptoquark types of the first generation (see section 8). Thus, leptoquarks allowed in the 200 to 300 GeV range must have interactions with lepton-quark pairs much weaker than the electromagnetic interaction (i.e.  $\lambda \ll 0.3$ ).

In generic models with an arbitrarily small branching ratio  $\beta(LQ \rightarrow eq)$ , the chances of a discovery at HERA increase as  $\lambda$  grows, as can be inferred from the actual HERA<sub>I</sub> and Tevatron<sub>I</sub> constraints shown in Fig. 4 [37].

The constraints on first-, second- and third-generation leptoquarks obtained from Tevatron and HERA experiments are summarized in Tables 3, 4 and 5. Tevatron experiments offer the best opportunity to search for second- and third-generation leptoquarks. At Tevatron<sub>I</sub>, masses below 202 GeV (99 GeV) are excluded for second(third)-generation scalar leptoquarks with  $\beta(LQ \rightarrow \mu q) = 1.0$  ( $\beta(LQ \rightarrow \tau q) = 1.0$ ). Above these excluded domains, HERA has access to leptoquarks of higher generations only in cases where lepton-flavour violating processes are allowed. These are discussed in detail in section 5. Striking event topologies could result from  $s$ - or  $u$ -channel exchange of leptoquarks if  $\lambda_{eq} \times \lambda_{\mu q} \neq 0$  or  $\lambda_{eq} \times \lambda_{\tau q} \neq 0$ .

Future prospects for HERA<sub>II</sub> and Tevatron<sub>II</sub> are illustrated in Fig. 5 [42] in the case of a first-

generation scalar leptoquark decaying into  $eq$ . Tevatron<sub>II</sub> will offer a better mass reach for  $\beta(LQ \rightarrow eq) \simeq 1$  while the sensitivity will be best at HERA<sub>II</sub> for  $\beta(LQ \rightarrow eq) \lesssim 0.5$  even for interaction strengths two orders of magnitude weaker than the electromagnetic interaction strength.

**Other lepton-parton exotics:**

For completeness, it should be mentioned that other exotic lepton-parton resonances have been discussed [43] in the context of  $ep$  colliders. Most prominent among these are leptogluons, which appear as colour-octet partners of the known (colour-singlet) leptons in composite models [44] in which the leptons are bound states of some coloured constituents. The leptoquark resonance-search results have been re-interpreted to establish constraints on leptogluon masses depending on a composite scale  $\Lambda$  in early search papers at HERA [32] but the subject has not been revisited recently.

F =2 Leptoquarks					F=0 Leptoquarks				
LQ Type	$Q_{em}$	$T_3$	LQ Decay	$\beta$	LQ Type	$Q_{em}$	$T_3$	LQ Decay	$\beta$
$S_{0,L}$	$-1/3$	0	$l_L^- u_L$	1/2	$V_{0,L}$	$-2/3$	0	$l_L^- \bar{d}_R$	1/2
			$\nu_L d_L$	1/2				$\nu_L \bar{u}_R$	1/2
$S_{0,R}$			$l_R^- u_R$	1	$V_{0,R}$			$l_R^- \bar{d}_L$	1
$\tilde{S}_{0,R}$	$-4/3$	0	$l_R^- d_R$	1	$\tilde{V}_{0,R}$	$-5/3$	0	$l_R^- \bar{u}_L$	1
$S_{1,L}$	$-4/3$	$-1$	$l_L^- d_L$	1	$V_{1,L}$	$-5/3$	$-1$	$l_L^- \bar{u}_R$	1
	$-1/3$	0	$l_L^- u_L$	1/2		$-2/3$	0	$l_L^- \bar{d}_R$	1/2
			$\nu_L d_L$	1/2				$\nu_L \bar{u}_R$	1/2
	$+2/3$	$+1$	$\nu_L u_L$	1		$+1/3$	$+1$	$\nu_L \bar{d}_R$	1
$V_{1/2,L}$	$-4/3$	$-1/2$	$l_L^- d_R$	1	$S_{1/2,L}$	$-5/3$	$-1/2$	$l_L^- \bar{u}_L$	1
$V_{1/2,R}$	$-4/3$		$l_R^- d_L$	1	$S_{1/2,R}$	$-5/3$		$l_R^- \bar{u}_R$	1
	$-1/3$	$+1/2$	$l_R^- u_L$	1		$-2/3$	$+1/2$	$l_R^- \bar{d}_R$	1
$\tilde{V}_{1/2,L}$	$-1/3$	$-1/2$	$l_L^- u_R$	1	$\tilde{S}_{1/2,L}$	$-2/3$	$-1/2$	$l_L^- \bar{d}_L$	1
	$+2/3$	$+1/2$	$\nu_L u_R$	1		$+1/3$	$+1/2$	$\nu_L \bar{d}_L$	1

Table 2: Leptoquarks with fermionic number  $|F| = 2$  (*left column*) and  $F = 0$  (*right column*) in the Buchmüller-Rückl-Wyler (BRW) effective model [8]. The scalar (S) and vector (V) leptoquarks (LQ) are grouped into weak-isospin families (subscript index). In the minimal BRW model, leptoquarks coupling to fermions (i.e. in lepton ( $l$ )-quark ( $q$ ) pairs) of different chiralities are assumed independent. Here, by convention [14], the leptoquark types are distinguished by the chirality ( $L, R$  index) of the coupled lepton. Also given for each leptoquark is the electric charge  $Q_{em}$ , the third component  $T_3$  of the weak isospin, their allowed decay modes and the corresponding branching fractions  $\beta$ . For simplicity, the same symbols are often used to designate both leptoquarks and anti-leptoquarks. Thus, for example, the  $S_{1,L}$  is used implicitly in the text for the leptoquark  $Q_{em} = -4/3$  ( $Q_{em} = -1/3$ ) involved in the production process  $e_L^- d_L \rightarrow S_{1,L}$  ( $e_L^- u_L \rightarrow S_{1,L}$ ) or in the conjugate processes  $e_R^+ \bar{d}_R \rightarrow S_{1,L}$  ( $e_R^+ \bar{u}_R \rightarrow S_{1,L}$ ). Note for instance that this  $S_{1,L}$  cannot be produced in the  $Q_{em} = +2/3$  state in a  $eq$  collision. Compared to the original BRW nomenclature [8], the “Aachen notations” [14] adopted here have the following correspondence:  $S_0 \leftrightarrow S_1^{BRW}$ ;  $\tilde{S}_0 \leftrightarrow \tilde{S}_1^{BRW}$ ;  $S_1 \leftrightarrow S_3^{BRW}$ ;  $V_{1/2} \leftrightarrow V_2^{BRW}$ ;  $\tilde{V}_{1/2} \leftrightarrow \tilde{V}_2^{BRW}$ ;  $V_0 \leftrightarrow U_1^{BRW}$ ;  $\tilde{V}_0 \leftrightarrow \tilde{U}_1^{BRW}$ ;  $V_1 \leftrightarrow U_3^{BRW}$ ;  $S_{1/2} \leftrightarrow R_2^{BRW}$ ;  $\tilde{S}_{1/2} \leftrightarrow \tilde{R}_2^{BRW}$ .

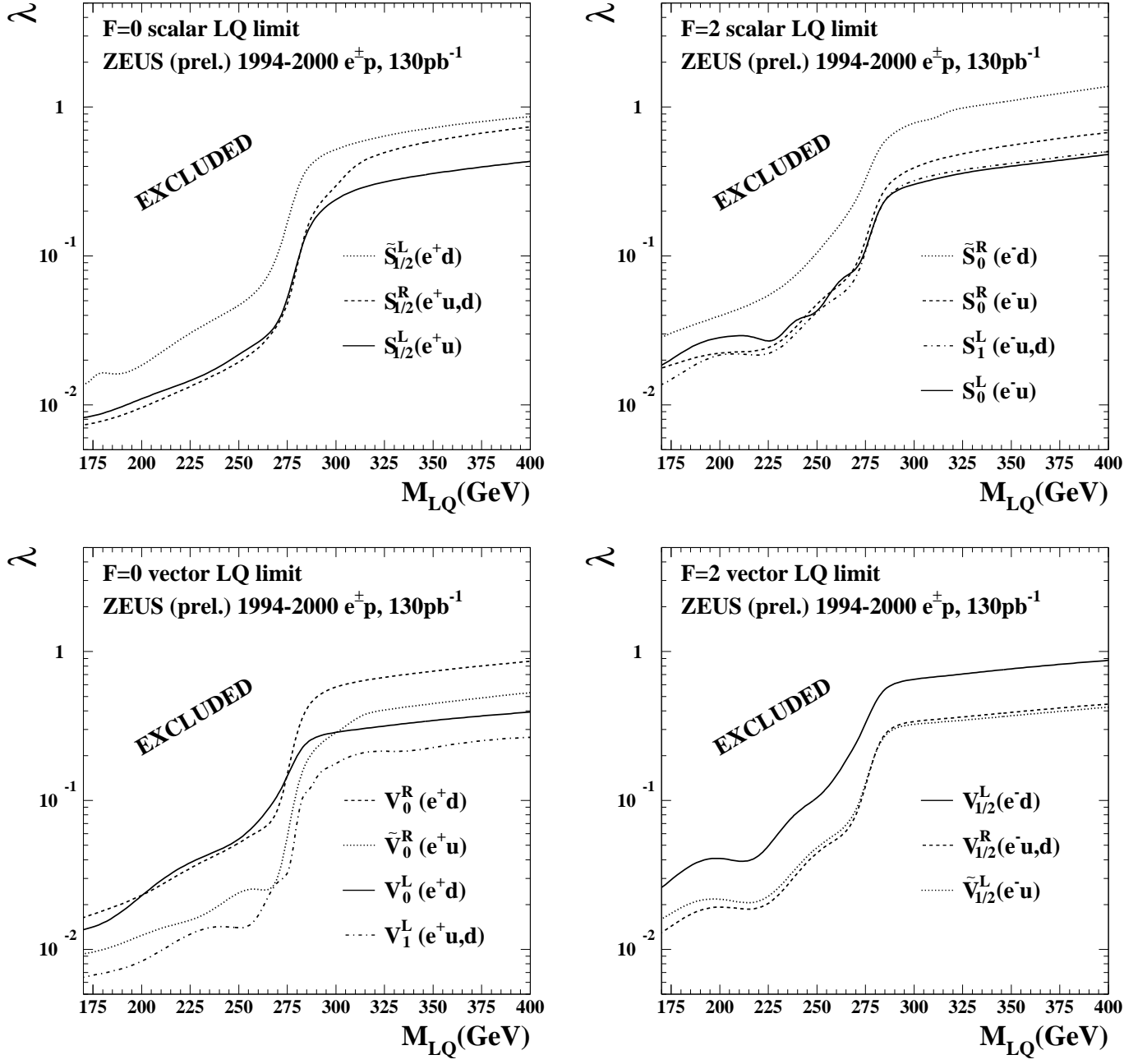


Figure 2: Exclusion limits obtained [39] at the HERA $_I$  collider in the  $\lambda$  vs.  $M_{LQ}$  plane for leptoquarks of the BRW model. Other recent leptoquark results from the H1 and ZEUS experiments using all available  $e^\pm p$  data from HERA $_I$  can be found in Refs. [36, 37, 38, 39].

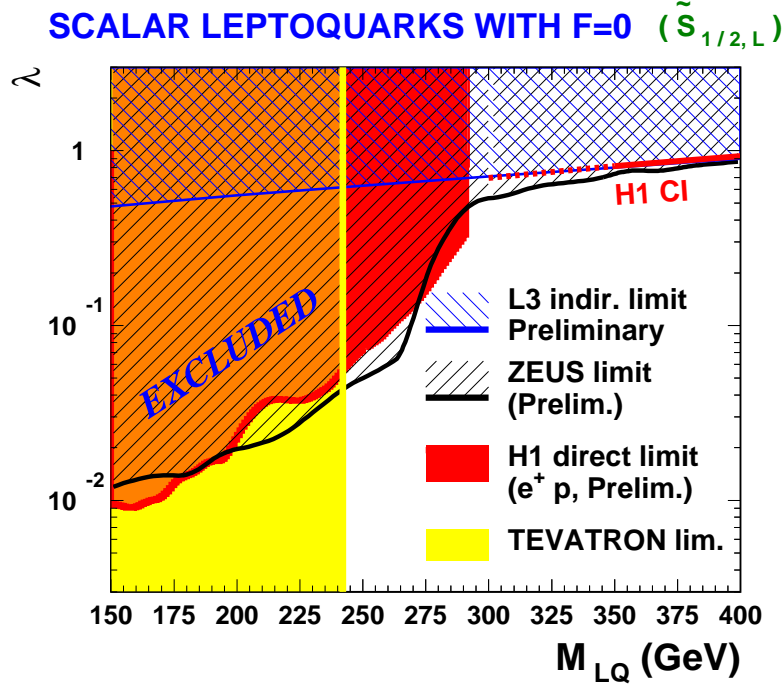


Figure 3: Existing collider constraints on a typical scalar leptoquark obtained at HERA, LEP (from L3 [40]) and Tevatron colliders in the Yukawa coupling *vs.* mass plane.

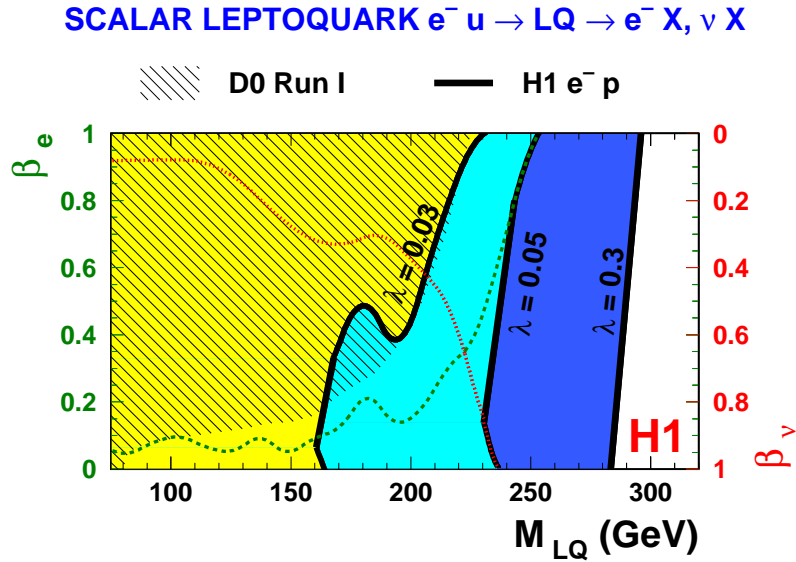


Figure 4: Comparison of the HERA and Tevatron bounds for generic scalar leptoquarks in the branching ratio *vs.* mass plane. The HERA bounds (from H1) are shown for three assumptions on Yukawa coupling  $\lambda$ . For  $\lambda = 0.05$ , limits using only  $eq$  final state (dashed line) and only  $\nu q$  final state (dotted line) are also shown.

COLLIDER CONSTRAINTS on 1 <sup>st</sup> GENERATION LEPTOQUARKS					
SCALARS					
$\beta_e$	Lower Mass Limits (in GeV) at 95%CL for			Assumptions	Experiment
	any $\lambda_{lq}$ values	$\lambda_{lq} \geq 0.1$	$\lambda_{lq} \geq 0.3$		
1	242	-	-	$p\bar{p} \rightarrow eeqq + X$	CDF $\oplus$ D $\emptyset$ [31]
	213	-	-		CDF [24]
	225	-	-		D $\emptyset$ [25]
	-	282	298	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	H1 [36]
	-	268	282	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	246	270	$e^+d \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	273	296	$e^-u \rightarrow LQ^{F=2} \rightarrow eq$	H1 [37]
	-	276	295	$e^-u \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
	-	243	276	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	H1 [37]
	-	249	278	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
1/2	204	-	-	$p\bar{p} \rightarrow e\nu qq(eeqq; \nu\nu qq) + X$	D $\emptyset$ [25]
	-	275	292	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	H1 [36]
	-	261	278	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	235	265	$e^+d \rightarrow LQ^{F=0} \rightarrow eq, \nu q$	ZEUS [35]
	-	262	289	$e^-u \rightarrow LQ^{F=2} \rightarrow eq, \nu q$	H1 [37]
	-	271	294	$e^-u \rightarrow LQ^{F=2} \rightarrow eq, \nu q$	ZEUS [38]
	-	230	270	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	H1 [37]
	-	231	271	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
0	98	-	-	$p\bar{p} \rightarrow \nu\nu qq + X$	D $\emptyset$ [25]
	-	237	262	$e^+d \rightarrow LQ^{F=0} \rightarrow \nu q$	ZEUS [35]
	-	262	282	$e^-u \rightarrow LQ^{F=2} \rightarrow \nu q$	H1 [37]
	-	268	293	$e^-u \rightarrow LQ^{F=2} \rightarrow \nu q$	ZEUS [38]

Table 3: Lower mass limits (95%CL) on first-generation scalar leptoquarks from direct searches at colliders for different decay branching fraction  $\beta_e$ . For  $\beta_e = 1/2$  limits, when both  $eq$  and  $\nu q$  decays are used,  $\beta_e + \beta_\nu = 1$  is assumed. The results from H1 and ZEUS experiments given here were derived in the context of generic models (with arbitrary  $\beta_e$ ) and depend on the Yukawa coupling  $\lambda_{lq}$  to lepton-quark pairs. Other results obtained in the strict context of the minimal BRW model are available from HERA (see text).



COLLIDER CONSTRAINTS on $1^{st}$ GENERATION LEPTOQUARKS						
VECTORS						
$\beta_e$	Lower Mass Limits (in GeV) at 95%CL for				Assumptions	Experiment
	LQ $\leftrightarrow$ boson couplings:		$\lambda_{lq} \geq 0.1$	$\lambda_{lq} \geq 0.3$		
	Min. Vec.	Yang-Mills				
1	292	345	-	-	$p\bar{p} \rightarrow eeqq + X$	DØ [25]
	-	-	272	283	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	-	264	292	$e^+d \rightarrow LQ^{F=0} \rightarrow eq$	H1 [36]
	-	-	241	271	$e^+d \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	-	275	295	$e^-u \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
	-	-	246	277	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
1/2	282	337	-	-	$p\bar{p} \rightarrow \nu qq(eeqq; \nu \nu qq) + X$	DØ [25]
	-	-	266	281	$e^+u \rightarrow LQ^{F=0} \rightarrow eq$	ZEUS [35]
	-	-	260	290	$e^+d \rightarrow LQ^{F=0} \rightarrow eq, \nu q$	H1 [36]
	-	-	239	267	$e^+d \rightarrow LQ^{F=0} \rightarrow eq, \nu q$	ZEUS [35]
	-	-	276	295	$e^-u \rightarrow LQ^{F=2} \rightarrow eq, \nu q$	ZEUS [38]
	-	-	230	271	$e^-d \rightarrow LQ^{F=2} \rightarrow eq$	ZEUS [38]
0	238	298	-	-	$p\bar{p} \rightarrow \nu \nu qq + X$	DØ [25]
	-	-	268	300	$e^+d \rightarrow LQ^{F=0} \rightarrow \nu q$	H1 [36]
	-	-	243	267	$e^+d \rightarrow LQ^{F=0} \rightarrow \nu q$	ZEUS [35]
	-	-	280	295	$e^-u \rightarrow LQ^{F=2} \rightarrow \nu q$	ZEUS [38]

Table 4: Lower mass limits (95%CL) on first-generation vector leptoquarks from direct searches at colliders for different decay branching fraction  $\beta_e$ . The results from CDF and DØ experiments depend on anomalous couplings to gauge bosons (see text) and are given here for “Yang-Mills” or “Minimal Vector” models. For  $\beta_e = 1/2$  limits, when both  $eq$  and  $\nu q$  decays are used,  $\beta_e + \beta_\nu = 1$  is assumed. The results from H1 and ZEUS experiments given here were derived in the context of generic models (with arbitrary  $\beta_e$ ) and depend on the Yukawa coupling  $\lambda_{lq}$  to lepton-quark pairs. Other results obtained in the strict context of the minimal BRW model are available from HERA (see text).

COLLIDER CONSTRAINTS on LEPTOQUARKS of HIGHER GENERATIONS					
2 <sup>nd</sup> Generation					
$\beta_\mu$	Lower Limits on LQ Mass (95%CL; in GeV) for			Assumptions	Experiment
	SCALARS	VECTORS			
		LQ $\leftrightarrow$ boson couplings:			
		Min. Vec.	Yang-Mills		
1	202	-	-	$p\bar{p} \rightarrow \mu\mu qq + X$	CDF [26]
1/2	200	275	325	$p\bar{p} \rightarrow \mu\mu qq + X$	DØ [27]
	160	-	-	$p\bar{p} \rightarrow \mu\mu qq + X$	CDF [26]
	180	260	310	$p\bar{p} \rightarrow \mu\nu qq(\mu\mu qq; \nu\nu qq) + X$	DØ [27]
0	123	171	222	$p\bar{p} \rightarrow \nu\nu cc + X$	CDF [28]
	98	238	298	$p\bar{p} \rightarrow \nu\nu qq + X$	DØ [25]
3 <sup>rd</sup> Generation					
$\beta_\tau$	Lower Limits on LQ Mass (95%CL; in GeV) for			Assumptions	Experiment
	SCALARS	VECTORS			
		LQ $\leftrightarrow$ boson couplings:			
		Min. Vec.	Yang-Mills		
1	99	170	225	$p\bar{p} \rightarrow \tau\tau qq + X$	CDF [29]
0	148	199	250	$p\bar{p} \rightarrow \nu\nu bb + X$	CDF [28]
	94	148*	216	$p\bar{p} \rightarrow \nu\nu bb + X, b \rightarrow \mu + X'$	DØ [30]

Table 5: Lower mass limits (95%CL) on second- and third-generation leptoquarks from direct searches at colliders for different decay branching fraction  $\beta_\mu$  and  $\beta_\tau$ . The results in the case of vector leptoquarks possibly depend on anomalous couplings to gauge bosons (see text) and are given here for “Yang-Mills” or “Minimal Vector” models (except for the result marked with a \* which was obtained for anomalous couplings leading to a minimal cross-section). For  $\beta_\mu = 1/2$  limits, when both  $\mu q$  and  $\nu q$  decays are used,  $\beta_\mu + \beta_\nu = 1$  is assumed. The limits for the third-generation quoted here assume no decays to top.

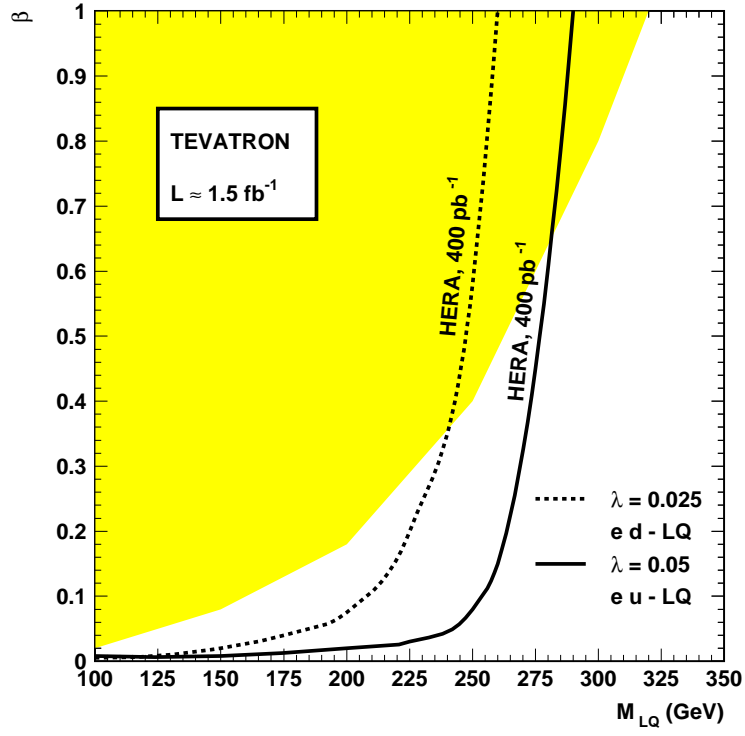


Figure 5: Prospect of mass-dependent sensitivities on the branching ratio  $\beta$  of a leptoquark decaying into  $eq$ , for  $1.5 \text{ fb}^{-1}$  of Tevatron<sub>II</sub> data and  $400 \text{ pb}^{-1}$  of HERA<sub>II</sub> data.

### 3 Alternative Theories for Electroweak Symmetry Breaking

The origin of ordinary particle masses remains a mystery. It is nevertheless a common belief that an electroweak symmetry breaking mechanism characterized by one (or more) scalar particles is responsible. Such particles could be elementary as in the Standard Model or in supersymmetric theories like Supergravity. Alternatively, our parametrization in terms of scalar couplings may in fact represent a low-energy manifestation of more fundamental dynamics, with additional particles and interactions. This is the underlying assumption of Technicolour or compositeness theories. Searches carried out in the framework of Technicolour theories, where specific dynamical assumptions are made, are discussed in subsection 3.1. The motivations for prospective studies carried out in the framework of the BESS (Breaking Electroweak Symmetry Strongly) model, which possesses new composite bosonic states, are discussed in subsection 3.2.

#### 3.1 Technicolour

The Technicolour theory was originally motivated by the premise that any fundamental energy scale, such as the scale of electroweak symmetry breaking, should have a dynamical origin. Thus, a dynamical electroweak symmetry breaking mechanism is implemented, in which a rôle similar to that of the Higgs boson in the Standard Model is now played by multiplets of technihadrons composed of fundamental techniquarks bound by a new Technicolour force.

The simplest Technicolour theories [45, 46] did not address the flavour problem and failed to explain lepton and quark masses. Moreover, such theories have now been excluded in particular by  $LEP_I$  constraints [47] on contributions to vacuum-polarization amplitudes [48]. In the Extended Technicolour (ETC) model [49], a new gauge interaction is introduced to couple ordinary quarks and leptons to technifermions. Thus, quarks and leptons acquire masses  $m_{q,l} \simeq \Lambda_{TC}^3/M_{ETC}^2$ , with  $\Lambda_{TC}$  of  $\mathcal{O}(10^{2-3})$  GeV, the characteristic scale of the new strong gauge interaction, and  $M_{ETC}$  of  $\mathcal{O}(10^5)$  GeV, the scale at which the ETC gauge group breaks down to flavour, colour and technicolour. But the ETC model in turn has severe problems with unwanted flavour-changing neutral current (FCNC) interactions.

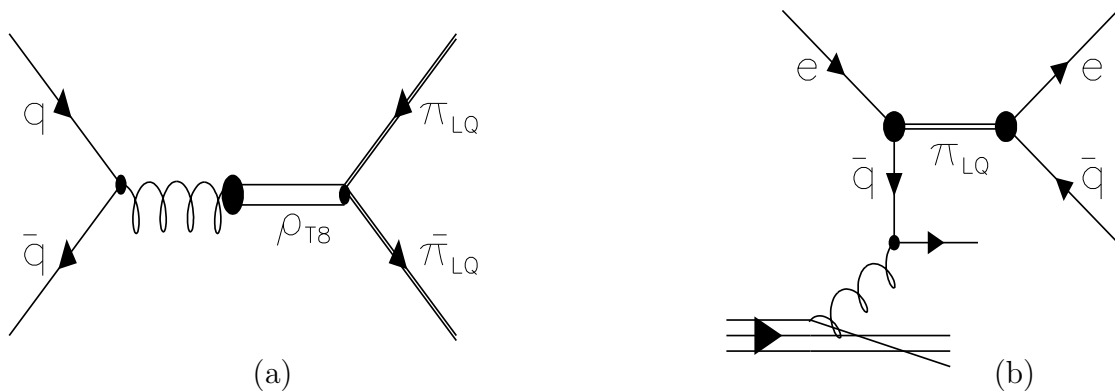


Figure 6: a) Diagram for production of technipion (“leptoquark”) pairs in hadronic collisions via  $s$ -channel production of a technirho. b) Diagram for single production of leptotriple involving heavy quarks in lepton-hadron collisions.

The FCNC problems of the ETC model are avoided in recent and more involved "Walking Technicolour" models [50, 51, 52]. This is achieved, at the expense of a loss in predictive power, by departing from the original QCD analogy and imposing that, in the presence of a large number of technifermions, the Technicolour gauge coupling runs much more slowly. The slow running of the coupling permits ordinary quark and lepton masses below  $\mathcal{O}(1)$  GeV to be generated from ETC interactions at  $\mathcal{O}(10^5)$  GeV. Walking Technicolour cannot be fully tested by precision experiments but it implies the existence of numerous Goldstone-boson bound states of the technifermions which should appear at masses of  $\mathcal{O}(10^{2-3})$  GeV and can be searched for at colliders. These include colour-singlet mesons (e.g. scalar technipions  $\pi_T^{\pm,0}$ ), colour-triplets (e.g.  $\pi_{LQ}$  leptoquarks) and colour-octets (e.g.  $\pi_{T8}^{\pm,0}$  technipions or  $\rho_{T8}$  technirhos). In contrast to the leptoquarks of the BRW model discussed in section 2, the  $\pi_{LQ}$ 's have Higgs-like couplings to ordinary fermions.

Searches for colour-non-singlet technimesons in the context of Walking Technicolour have been performed at the Tevatron<sub>I</sub> [53, 28] collider based on the model assumptions of Lane and Ramana [54]. The constraints thus established appear particularly relevant in view of future data taking at Tevatron<sub>II</sub> and HERA<sub>II</sub>. These are reviewed in the following. Otherwise, general reviews of existing bounds on technihadrons at colliders can be found in literature [55, 56].

Resonant production of colour-octet technirhos can proceed in  $p\bar{p}$  collisions through  $q\bar{q}$ ,  $gg \rightarrow (g \leftrightarrow \rho_{T8})$  followed by the decay of the  $\rho_{T8}$  via  $\rho_{T8} \rightarrow \pi_{T8}\bar{\pi}_{T8}, \pi_{LQ}\bar{\pi}_{LQ}$  or via e.g.  $\rho_{T8} \rightarrow q\bar{q}, gg'$ . An example diagram is shown in Fig. 6(a).

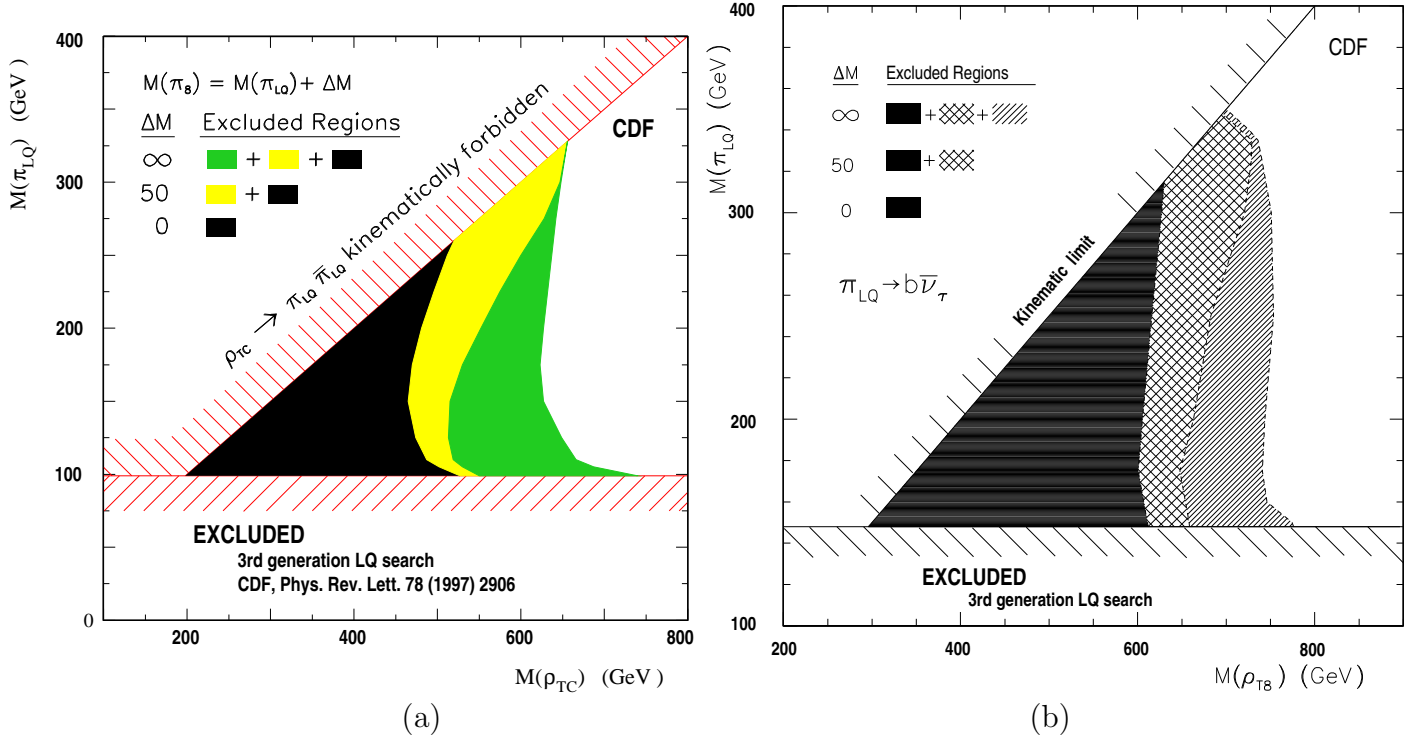


Figure 7: Technicolour constraints (95% CL) from the CDF experiment at the Tevatron. a) Excluded regions for various  $M(\pi_{T8}) - M(\pi_{LQ})$  assumptions from a search for  $\rho_{T8} \rightarrow \pi_{LQ}\pi_{LQ} \rightarrow \tau^+\tau^-jj$ ; (from [53]). b) Excluded regions for various  $M(\pi_{T8}) - M(\pi_{LQ})$  assumptions from a search for  $\rho_{T8} \rightarrow \pi_{LQ}\pi_{LQ} \rightarrow b\bar{b}\nu\bar{\nu}$ ; (from [28]).

The CDF experiment has searched for  $\rho_{T8}$  production followed by the decay  $\rho_{T8} \rightarrow \pi_{LQ} \bar{\pi}_{LQ}$ , taking into account the (unobserved) branching fraction of  $\rho_{T8} \rightarrow \pi_{T8} \bar{\pi}_{T8}$ . The leptoquark technipions were assumed to decay either via  $\pi_{LQ} \rightarrow \tau^+ b$ , in which case the analysis has imposed no  $b$  tagging (Fig. 7a) or via  $\pi_{LQ} \rightarrow \nu b$  in which case  $b$  tagging is imposed (Fig. 7b). Thus, the analysis is common to that of searches of generic third-generation leptoquarks produced in pairs (section 2) which sets a lower bound on the mass  $M(\pi_{LQ})$  independent of  $M(\rho_{T8})$ . The constraints from  $\rho_{T8}$  production which extends beyond this lower bound are shown in Fig. 7 in the  $M(\pi_{LQ})$  vs.  $M(\rho_{T8})$  plane for various  $\Delta M = M(\pi_{T8}) - M(\pi_{LQ})$  assumptions. Provided that  $M(\pi_{T8}) > 2 \times M(\pi_{LQ})$ , colour-octet technirhos are excluded at 95% CL for masses up to  $M(\rho_{T8}) < 600 \text{ GeV}$  independently of  $\Delta M$ .

Leptoquark technipions could be singly produced in  $ep$  collisions via a  $t$ -channel diagram as shown in Fig. 6(b), preferably involving a heavy quark  $b$  generated by  $g \rightarrow b\bar{b}$  splitting. It should be noted that such a process, which requires at production an  $(eb)$ -type of lepton-quark coupling [57], could turn out to be strongly suppressed in Technicolour theories by interfamily mixing parameters. Possible production and decay modes (including lepton-flavour violating processes such as  $e + p \rightarrow e + \pi_{LQ} + \bar{b} + X$ ;  $\pi_{LQ} \rightarrow \tau + b$ ) were discussed for  $ep$  colliders in the context of early Technicolour theories some 20 years ago in [58]. Unfortunately the topic has not been revisited. Lepton-flavour conserving  $(eb)$ -type of leptoquarks [57] would be confronted to the stringent Tevatron constraints obtained for first-generation leptoquarks unless their dominant decay were to be into  $\nu_e t$ .

In any case, the Technicolour constraints of Fig. 7 from the Tevatron incidentally push leptoquark technipions beyond the reach of HERA, unless, as is likely in Walking Technicolour, the  $\rho_{T8} \rightarrow \pi_{LQ} \bar{\pi}_{LQ}$  decay is kinematically not allowed. Even then, for most models, very stringent bounds can be deduced from Tevatron data; for instance from the absence of dijet resonances if the  $\rho_{T8}$  decays dominantly into  $q\bar{q}$  or  $gg'$  pairs. It is nevertheless possible that the dijet rate itself could be depleted [55] if, for instance, the  $\rho_{T8}$  decays dominantly through  $\rho_{T8} \rightarrow g\pi_{T8}$ ;  $\pi_{T8} \rightarrow q\bar{q}$ . In such a case, the relevant bound from CDF is the third-generation leptoquark bound at 99 GeV (95% CL), beyond which HERA<sub>II</sub> could have a sensitivity for  $t$ -channel  $\pi_{LQ}$  production [57, 58]. A richer set of other possible signals are being explored for Tevatron<sub>II</sub>.

## 3.2 The BESS Model

On the basis of unitarity arguments, it is widely believed that, in the absence of a light Higgs boson or other low-lying scalar resonances, the interaction among electroweak gauge bosons must become strong at high energies. In other words, in the absence of an elementary Higgs boson, new physics should in any case become manifest in the gauge-boson sector at the electroweak symmetry breaking characteristic scale of typically  $\Lambda_{EWSB} = 4\pi v \simeq 3 \text{ TeV}$ .

Avoiding the difficult task of constructing a viable dynamical scheme, the idea of a strongly interacting sector as responsible for electroweak symmetry breaking can be tested through an effective-Lagrangian approach. This is the motivation for the searches carried out in the framework of the so-called BESS model.

In its minimal version [59], the BESS model contains a triplet of new vector resonances  $V^{\pm,0}$  similar to the  $\rho$  or techni- $\rho$  of Technicolour models. These new vector bosons mix with the electroweak gauge bosons. The mixing depends on the ratio  $g/g''$  where  $g$  is the  $SU(2)_L$  Standard Model coupling and  $g''$  is the new gauge coupling entering the self-coupling of the  $V^{\pm,0}$ . The coupling of the  $V^{\pm,0}$  to ordinary fermions is fixed by introducing a parameter  $b$ . Besides  $g''$  and  $b$ , the model also requires

a characteristic mass scale  $M$  which might be taken as the mass  $M_V$  of the new strongly interacting bosons. The Standard Model is recovered in the limit  $g'' \rightarrow 0$  and  $b \rightarrow 0$ . Specific versions of the BESS model can be made to mimic Technicolour models.

Constraints on the parameters  $g/g''$  and  $b$  of the BESS model have been established by combining precision electroweak data from the LEP and SLC colliders with  $M_{top}$  and  $M_W$  measurements from Tevatron experiments [60]. The prospects for direct  $V$  resonant production via  $l^+l^-$  or  $q\bar{q}$  annihilation (through  $b$  or due to mixing) and via  $WW$  fusion have been studied for future multi-TeV colliders in the case of a minimal BESS model in Ref. [61].

A particular BESS model that has received attention for collider physics is the so-called degenerate-BESS model [62, 63] (d-BESS) which requires two new triplets of gauge bosons  $L^{\pm,0}$  and  $R^{\pm,0}$  quasi-degenerate in mass. A main property of the d-BESS model is that all deviations at low energy [i.e.  $\mathcal{O}(M_Z)$ ] from Standard Model expectations are completely suppressed. Thus, a sensitivity to new strongly interacting bosons could even be possible at existing colliders despite the constraints of precision electroweak tests [62, 63].

A full description of the effective Lagrangian for the d-BESS model relevant at colliders can be found in Ref [63]. A gold-plated signature of the model at hadronic colliders would be a pair of leptons originating from the decay of new bosons resonantly produced in  $q\bar{q}'$  annihilation processes. In the charged channel for instance, the process  $p\bar{p} \rightarrow L^\pm + X \rightarrow e\nu_e(\mu\nu_\mu) + X$  would lead to a Jacobian peak in the transverse-mass distribution of final state leptons lying on a background continuum from standard Drell-Yan processes with  $W$  propagator. In the neutral channel, the cleanest signal would be provided by the process  $p\bar{p} \rightarrow L^0(R^0) + X \rightarrow e^+e^- + X$ . The signal would appear as a narrow resonance in the invariant-mass distribution of final state electrons lying on a background continuum from  $\gamma^*$  and  $Z^*$  production. It has been shown [64] that experiments at Tevatron<sub>II</sub> will be sensitive to an unexplored range of  $g/g''$  values for characteristic mass scales  $M$  in the range  $200 \text{ GeV} < M < 1 \text{ TeV}$  via  $L^\pm$  searches. In contrast, the HERA experiments cannot improve on existing constraints, as was examined in Ref. [65].

## 4 Supersymmetry

### 4.1 Introduction: Supersymmetric Matter and Model Parameters

The search for supersymmetry (SUSY) has constituted one of the central themes in theoretical and experimental high energy physics over the past decades. Supersymmetry was originally introduced [66] in the framework of relativistic field theories as the only possible remaining non-trivial extension of the Poincaré group (which contains space-time translations and Lorentz transformations), relating fermionic with bosonic fields through its algebraic structure. Supersymmetric models provide a consistent framework for the unification of gauge interactions at some Grand Unification (GUT) scale while resolving the “hierarchy problem”, i.e. explaining the stability of the electroweak energy scale,  $\mathcal{O}(10^2)$  GeV, relative to the GUT scale ( $M_{GUT} \simeq 10^{16}$  GeV) in the presence of quantum corrections. It furthermore stabilizes a low Higgs mass against radiative corrections, provided that the characteristic mass scale of SUSY is below  $\mathcal{O}(1)$  TeV.

Yet, the existence of any particular realisation of SUSY in Nature remains to be proven (or falsified !). Excellent and comprehensive review articles have been written on this topic recently, exploring in particular the aftermath of LEP precision data [67, 68, 69]. Our goal here is more modest as we shall review those aspects most relevant for experimental searches at the HERA<sub>II</sub> and Tevatron<sub>II</sub> colliders, following a brief introduction on some essential aspects of SUSY models.

#### Minimal Sparticle Spectrum:

An immediate consequence of the algebraic structure of supersymmetry is that particles belonging to the same supermultiplet must have the same mass. However, the experimental constraints clearly forbid the existence of, say, a scalar with a mass equal to that of the electron. Known bosons cannot be made to be superpartners of known fermions. They do not appear to have very much in common, with different gauge-symmetry properties and a number of known degrees of freedom significantly larger for fermions. Hence supersymmetry, if it exists in the physical world, must be broken. It requires the introduction of new heavy bosonic (fermionic) partners that ought to be associated with each of the ordinary quarks and leptons (gauge bosons and the Higgs bosons). A supersymmetric extension of the Standard Model with minimal new particle content requires in addition the introduction of two Higgs-field doublets,  $H_1$  and  $H_2$ .

Ultimately, the number of free parameters of the new theory and the details of the observable phenomenology will depend on the supersymmetry-breaking mechanism chosen by Nature (see below) and on the absence or presence of  $R$ -parity-violating interactions (see below). However, the minimal particle content of supersymmetric extensions of the Standard Model is essentially common to all models and summarised in Table 6.

To a given fermion,  $f$ , corresponds a superpartner for each of its chirality states. These  $\tilde{f}_L$  and  $\tilde{f}_R$  are fundamentally independent fields. They are expected to mix significantly only in the third generation, leading to the mass eigenstates  $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$  and  $\tilde{b}_2$ .

The “neutralinos”  $\tilde{\chi}_{1,2,3,4}^0$  (“charginos”  $\tilde{\chi}_{1,2}^\pm$ ) are the mass eigenstates resulting from the mixing of the non-strongly interacting gauginos,  $\tilde{\gamma}$  and  $\tilde{Z}$  ( $\tilde{W}^\pm$ ), with the higgsinos,  $\tilde{H}_1^0$  and  $\tilde{H}_2^0$  ( $\tilde{H}^\pm$ ).

The two Higgs doublets lead to five physical Higgs bosons, two CP-even neutral scalars ( $h^0, H^0$ ), a CP-odd neutral pseudo-scalar ( $A^0$ ) and a pair of charged scalars ( $H^\pm$ ).



<i>SUSY Physical States After Electroweak Symmetry Breaking</i>					
$R_P = +1$			$R_P = -1$		
Name	Symbol	Spin	Name	Symbol	Spin
<i>Ordinary Standard Model Matter</i>			<i>Supersymmetric Matter</i>		
leptons	$e, \nu_e$	1/2	sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
	$\mu, \nu_\mu$	1/2		$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	0
	$\tau, \nu_\tau$	1/2		$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau L}$	0
quarks	$u, d$	1/2	squarks	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$	0
	$c, s$	1/2		$\tilde{c}_L, \tilde{c}_R, \tilde{s}_L, \tilde{s}_R$	0
	$t, b$	1/2		$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	0
gluons	$g$	1	gluino	$\tilde{g}$	1/2
photon	$\gamma$	1	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
electroweak bosons	$Z^0$	1		$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	1/2
	$W^\pm$	1	charginos		
<i>Higgs Sector</i>					
<i>CP</i> -even scalars	$h^0, H^0$	0			
<i>CP</i> -odd pseudoscalars	$A^0$	0			
charged scalars	$H^\pm$	0			

Table 6: *Minimal particle content of Supersymmetric Standard Models.*

Needless to say, searches for the vast number of new “sparticles” and for the other indirect effects predicted by supersymmetric models have constituted a major analysis activity at high-energy colliders over the past decade. This is likely to remain so at the HERA<sub>II</sub> and Tevatron<sub>II</sub> colliders. If realized at low energies, and not yet found by then, it is widely believed that Nature cannot hide SUSY beyond the expected experimental sensitivity of the future LHC collider.

### Supersymmetry Breaking Mechanisms and Model Parameters:

How supersymmetry is broken and in which way this breaking is communicated to the particles remains an open question on the theoretical side. The phenomenology at colliders will depend strongly on the chosen answer.

In the so-called Minimal Supersymmetric Standard Model (MSSM),  $R$ -parity is assumed to be conserved and the SUSY breaking is simply parametrized by introducing explicitly “soft” terms in the effective Lagrangian [70]. For phenomenological studies, the sfermion masses are generally treated as free parameters while the masses of the neutralinos and charginos, as well as the gauge couplings between any two sparticles and a standard fermion or boson, are determined by a set of five parameters: the three soft-breaking parameters  $M_1$ ,  $M_2$  and  $M_3$  for the  $U(1)$ ,  $SU(2)$  and  $SU(3)$  gauginos, the ratio  $\tan\beta$  of the vacuum expectation values of the two neutral Higgs bosons, and the “mass” term  $\mu$  which mixes the Higgs superfields. The SUSY-breaking soft terms also contain in general bilinear ( $B$ ) and trilinear ( $A_{ijk}$ ) couplings.

However, one could expect that, if SUSY is a fundamental symmetry of Nature, then it should preferably be an exact symmetry which is spontaneously broken. In other words, the ultimate theory

should have a Lagrangian density that is invariant under SUSY but a vacuum that isn't. The symmetry would be hidden at low (collider) energies in a way analogous to the fate of electroweak symmetry in the ordinary Standard Model. Three prominent schemes have been extensively considered: Minimal Supergravity (mSUGRA), Gauge Mediated (GMSB) and Anomaly Mediated (AMSB) SUSY Breaking Models.

In Supergravity theories [71], the supersymmetry is broken in a “hidden” sector and the breaking is transmitted to the “visible” sector by gravitational interactions. In mSUGRA, masses and couplings must obey unification conditions at the GUT scale,  $M_{GUT} \simeq 10^{16}$  GeV. The gaugino masses  $M_1$ ,  $M_2$  and  $M_3$  unify to a common mass  $m_{1/2}$ ; scalar particles (sfermions and Higgs bosons) have a common mass  $m_0$  and all trilinear coupling parameters  $A_{ijk}$  have a common value  $A_0$ . Furthermore, the mass mixing parameter  $\mu$  can be expressed as a function of the other parameters via equations corresponding to the minimization of the Higgs potential when invoking radiative electroweak symmetry breaking, so that only the sign of  $\mu$  remains free. Thus, in mSUGRA, one is left with five unknowns (four free parameters and a sign), namely  $m_{1/2}$ ,  $m_0$ ,  $A_0$ ,  $\tan \beta$  and the sign of  $\mu$ . The measurements of the sparticle spectrum and SUSY phenomenology at collider energies could provide an overconstrained determination of these parameters at the GUT scale through renormalization group equations. In large domains of the parameter space, the lightest neutralino acts as the LSP (lightest supersymmetric particle) appearing at the end of the gauge-decay chains of other SUSY particles.

In GMSB models [72], the SUSY breaking is transmitted through gauge interactions via some messenger states of mass  $M \ll M_{Planck}$ . These models depend on the free parameters  $M_{mess}$ ,  $N_{mess}$ ,  $\Lambda$  and the sign of  $\mu$  where  $M_{mess}$  is the messenger scale,  $N_{mess}$  is an index depending on the chosen structure of the messenger sector, and  $\Lambda$  is a universal SUSY-breaking scale. If the SUSY breaking occurs at relatively low energy scales, e.g.  $\Lambda \sim \mathcal{O}(10^{1-2})$  TeV, then a very light gravitino ( $\tilde{G}$ ) will act as the LSP appearing at the end of the gauge-decay chains of other SUSY particles.

In AMSB models [73], the SUSY breaking is not transmitted directly from the “hidden” to the “visible” sector. The gaugino masses are rather generated at one loop as a consequence of the “super-Weyl” anomaly and depend on the mass parameter  $m_{3/2}$ . In minimal models, a universal scalar mass  $m_0$  is introduced at the GUT scale, leaving four unknowns (three free parameters and a sign),  $m_0$ ,  $m_{3/2}$ ,  $\tan \beta$  and the sign of  $\mu$ . The wino acts as the LSP and the lightest chargino and neutralino are nearly degenerate in mass.

## ***R*-parity and the Phenomenology:**

In the Standard Model, the conservation of the baryon and lepton number is an automatic consequence of the gauge invariance and renormalizability. In contrast, baryon and lepton number are no longer protected in supersymmetric extensions of the Standard Model. The introduction of a scalar (fermionic) partner for each ordinary fermion (boson) allows in general for new interactions that do not preserve baryon or lepton number. Such interactions can be avoided in an *ad hoc* manner by the introduction of a discrete symmetry implying the conservation of the quantum number  $R_p$  (*R*-parity) which distinguishes ordinary particles ( $R_p = +1$ ) from supersymmetric particles ( $R_p = -1$ ), and is defined as  $R_p \equiv (-1)^{3B+L+2S}$  with  $S$  denoting the particle spin,  $B$  the baryon number and  $L$  the lepton number.

Whether or not  $R_p$  is conserved in supersymmetric models has dramatic observable consequences. If  $R_p$  is exactly conserved then sparticles can only be produced in pairs and the LSP is absolutely stable.

The LSP is then a natural candidate for Cold Dark Matter in cosmology. At collider experiments the (cascade) decays of pair-produced heavy sparticles would always leave a pair of LSPs escaping detection, thus leading to a characteristic “missing energy-momenta” signal.

Reviews of the phenomenology relevant for collider physics from  $R_p$ -conserving supersymmetry can be found in the case of the MSSM/mSUGRA models in Refs. [67, 68, 69], for GMSB models in Refs. [74] and for AMSB models in Refs. [75].

If  $R_p$ -violating ( $\mathcal{R}_p$ ) interactions are allowed, then all supersymmetric matter becomes intrinsically unstable, sparticles can be singly produced and spectacular processes with lepton- or baryon-number violation could be observed at colliders.

The most general renormalizable  $R_p$ -violating superpotential consistent with the gauge symmetry and field content of the MSSM contains bilinear and trilinear terms:

$$W_{\mathcal{R}_p} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c ,$$

where an implicit summation over the generation indices,  $i, j, k = 1, 2, 3$ , and over gauge indices is understood. The  $\mu_i$  associated to fermion bilinears are dimensionful mixing parameters and the  $\lambda, \lambda'$ , and  $\lambda''$  are Yukawa-like couplings which are trilinear in the fields. The corresponding Lagrangian expanded in terms of four-component Dirac spinors is written as

$$\mathcal{L}_{L_i L_j E_k^c} = -\frac{1}{2} \lambda_{ijk} \left( \tilde{\nu}_{iL} \bar{l}_{kR} l_{jL} + \tilde{l}_{jL} \bar{l}_{kR} \nu_{iL} + \tilde{l}_{kR}^* \bar{\nu}_{iR}^c l_{jL} - (i \leftrightarrow j) \right) + \text{h.c.},$$

where for instance  $\bar{\nu}_{iR}^c = \overline{(\nu_i^c)_R}$ . Similarly,

$$\mathcal{L}_{L_i Q_j D_k^c} = -\lambda'_{ijk} \left( \tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + \tilde{d}_{kR}^* \bar{\nu}_{iR}^c d_{jL} - \tilde{l}_{iL} \bar{d}_{kR} u_{jL} - \tilde{u}_{jL} \bar{d}_{kR} l_{iL} - \tilde{d}_{kR}^* \bar{l}_{iR}^c u_{jL} \right) + \text{h.c.},$$

and

$$\mathcal{L}_{U_i^c D_j^c D_k^c} = -\frac{1}{2} \lambda''_{ijk} \left( \tilde{u}_{iR}^* \bar{d}_{jR} d_{kL}^c + \tilde{d}_{jR}^* \bar{u}_{iR} d_{kL}^c + \tilde{d}_{kR}^* \bar{u}_{iR} d_{jL}^c \right) + \text{h.c.} .$$

Now gauge invariance enforces antisymmetry of the  $\lambda_{ijk}$  couplings in their first two indices (i.e.  $\lambda_{ijk} = -\lambda_{jik}$ ), and antisymmetry of the  $\lambda''_{ijk}$  couplings in their last two indices (i.e.  $\lambda''_{ijk} = -\lambda''_{ikj}$ ). Hence, altogether there exist 45 dimensionless Yukawa couplings, 9  $\lambda_{ijk}$  plus 27  $\lambda'_{ijk}$  which break the conservation of lepton number and 9  $\lambda''_{ijk}$  which break baryon-number conservation. Basic tree diagrams illustrating the three types of Yukawa couplings are shown in Fig. 8.

The lepton-number violating ( $\mathcal{L}$ ) term  $\text{LLE}$  couples sleptons and leptons through  $\lambda$ . The  $\mathcal{LQ}$  term  $\text{LQD}$  couples squarks to lepton-quark pairs and sleptons to quark pairs through  $\lambda'$ . The baryon-number violating ( $\mathcal{B}$ ) term  $\text{UDD}$  couples squarks to quark pairs through  $\lambda''$ . Testing  $2^{45} - 1$  possible combinations of  $\lambda, \lambda'$  and  $\lambda''$  couplings of comparable size would obviously be an insurmountable task. The problem is partially reduced when taking into account constraints already established. The preservation of proton stability imposes for instance very stringent constraints on the co-existence of  $\mathcal{L}$  and  $\mathcal{B}$  couplings. The coupling products  $\lambda \times \lambda'$  and  $\lambda' \times \lambda''$  must essentially vanish. It is moreover reasonable to assume that

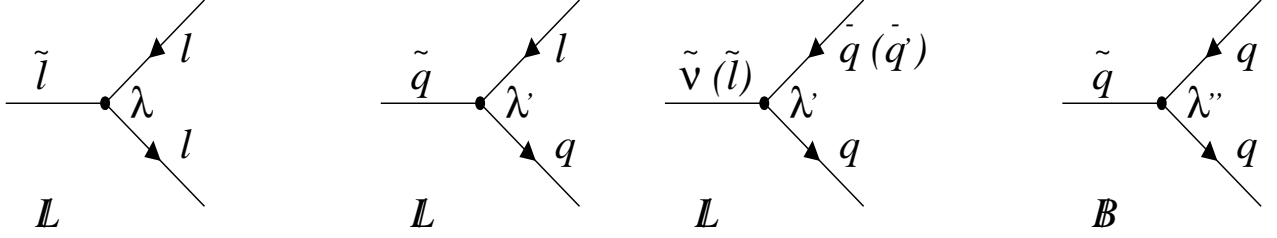


Figure 8: Basic tree diagrams for sfermion-fermion-fermion  $\mathcal{R}_p$  Yukawa interactions via  $\lambda, \lambda'$  and  $\lambda''$ .

there could be a strong hierarchy among the couplings, not unlike that observed in the Yukawa sector of the Standard Model. Thus, in actual searches it is generally assumed (conservatively !) that a single  $\lambda, \lambda'$  or  $\lambda''$  coupling dominates.

The discovery mass reach for sfermions at colliders can be considerably enlarged by single sparticle real production or virtual exchange involving  $\mathcal{R}_p$  Yukawa couplings. For sfermions masses below the available centre-of-mass energies ( $\sqrt{s}$ ) at a given collider,  $s$ -channel resonant processes are allowed with a production rate scaling with the Yukawa coupling squared. The list of the  $s$ -channel processes allowed at lowest order in  $e^+e^-$ ,  $ep$  and  $p\bar{p}$  collisions is given in Table 7. The  $\mathcal{L}$  coupling  $\lambda$  allows for  $s$ -channel

Resonant Production of Sfermions at Colliders (lowest-order processes)			
Collider	Coupling	Sfermion Type	Elementary Process
$e^+e^-$	$\lambda_{1j1}$	$\tilde{\nu}_\mu, \tilde{\nu}_\tau$	$l_i^+ l_k^- \rightarrow \tilde{\nu}_j \quad i = k = 1, j = 2, 3$
$p\bar{p}$	$\lambda'_{ijk}$	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	$d_k \bar{d}_j \rightarrow \tilde{\nu}_i \quad i, j, k = 1, \dots, 3$
		$\tilde{e}, \tilde{\mu}, \tilde{\tau}$	$u_j \bar{d}_k \rightarrow \tilde{l}_{iL} \quad i, k = 1, \dots, 3, j = 1, \dots, 2$
	$\lambda''_{ijk}$	$\tilde{d}, \tilde{s}, \tilde{b}$	$\bar{u}_i \bar{d}_j \rightarrow \tilde{d}_k \quad i, j, k = 1, \dots, 3, j \neq k$
		$\tilde{u}, \tilde{c}, \tilde{t}$	$\bar{d}_j \bar{d}_k \rightarrow \tilde{u}_i \quad i, j, k = 1, \dots, 3, j \neq k$
$ep$	$\lambda'_{1jk}$	$\tilde{d}_R, \tilde{s}_R, \tilde{b}_R$	$l_1^- u_j \rightarrow \tilde{d}_{kR} \quad j = 1, 2$
	$\lambda'_{1jk}$	$\tilde{u}_L, \tilde{c}_L, \tilde{t}_L$	$l_1^+ d_k \rightarrow \tilde{u}_{jL} \quad i, j, k = 1, \dots, 3$

Table 7: Sfermions  $s$ -channel resonant production at colliders. Charge conjugate processes (not listed here) are also possible. Real  $\tilde{\nu}$  production at an  $e^+e^-$  collider can only proceed via  $\lambda_{121}$  or  $\lambda_{131}$  while virtual  $\tilde{\nu}$  exchange in the  $t$ -channel is possible for any  $\lambda_{ijk}$  provided either  $i, j$  or  $k = 1$ . Real  $\tilde{q}$  production at an  $ep$  collider is possible via any of the nine  $\lambda'_{1jk}$  couplings.

resonant production of  $\tilde{\nu}$  at  $l^+l^-$  colliders. The  $\mathcal{L}$  coupling  $\lambda'$  allows for  $s$ -channel resonant production

of  $\tilde{q}$  at  $ep$  colliders and of  $\tilde{\nu}$  or  $\tilde{l}^\pm$  at  $p\bar{p}$  colliders. The  $\mathcal{B}$  coupling  $\lambda''$  allows for  $s$ -channel resonant production of  $\tilde{q}$  at  $pp$  colliders.

Virtual exchange involving  $\mathcal{R}_p$  couplings provides a sensitivity to sfermions with masses above the available  $\sqrt{s}$  at colliders. In the simplest process, the virtual exchange will provide a contribution to fermion pair production with a cross-section depending on the square of the Yukawa coupling squared. For  $M_{\tilde{f}} \gg \sqrt{s}$ , this will effectively contract to a four-fermion contact interaction (see section 8). At an  $e^+e^-$  collider, lepton-pair production can receive a contribution involving  $\lambda$  from  $s$ -channel exchange of  $\tilde{\nu}_\mu$  and  $\tilde{\nu}_\tau$  and from  $t$ -channel exchange of  $\tilde{\nu}_e$ ,  $\tilde{\nu}_\mu$  and  $\tilde{\nu}_\tau$ . Quark-pair production can receive a contribution involving  $\lambda'$  from  $t$ -channel exchange of  $\tilde{u}_L$ -like or  $\tilde{d}_R$ -like squarks. At an  $ep$  collider,  $s$ - and  $t$ -channel exchange of  $\tilde{u}_L$ -like or  $\tilde{d}_R$ -like squarks involving  $\lambda'$  can contribute to lepton-quark pair production. At a  $p\bar{p}$  collider, quark pair production can receive a contribution involving  $\lambda'$  from  $\tilde{\nu}$  or  $\tilde{l}$  exchange in the  $s$ -channel. It can also receive a contribution involving  $\lambda''$  from  $\tilde{q}$  exchange in the  $s$ - or  $t$ -channel.

The presence of an  $\mathcal{R}_p$  coupling will open new decay modes for sparticles. “Direct”  $\mathcal{R}_p$  decays will compete with “indirect” decays initiated by gauge couplings and in which the  $\mathcal{R}_p$  couplings enter at a later stage in the decay chain. The coupling  $\lambda$  allows for direct decays of sleptons into lepton pairs, and of gaugino-higgsinos into three leptons. The coupling  $\lambda'$  allows for direct decays of sleptons into quark pairs, of squarks into lepton-quark pairs, and of gaugino-higgsinos into a lepton plus a quark pair. The coupling  $\lambda''$  allows for direct decays of squarks into quark pairs, and of gaugino-higgsinos into three quarks.

## 4.2 Status of Supersymmetry Searches at Colliders

The precision measurements at LEP have left, as a legacy, at least indirect hints suggesting that supersymmetry could hide just above existing direct constraints. One such hint comes from the precisely measured gauge couplings, which are found to be consistent with a supersymmetric GUT provided that the sparticle masses are less than  $\mathcal{O}(1)$  TeV. Another hint comes from the precision electroweak data which suggest the existence of a relatively light neutral Higgs boson. The existence of a light neutral Higgs boson is a strong requirement in all supersymmetric models. A Standard Model fit [76] to these electroweak precision data provides an upper indirect limit of  $M_H \leq 193$  GeV (95% CL). The direct search at LEP<sub>II</sub> gives a lower limit of  $M_H \geq 114.4$  GeV (95% CL) [77]. The limits also apply at small  $\tan\beta$ , in the framework of the MSSM, to the light CP-even neutral Higgs boson  $h^0$ . Scanning over the parameter space of the MSSM gives [78] a conservative lower limit from LEP<sub>II</sub> of  $M_{h^0} > 91.0$  GeV.

No direct evidence for the existence of supersymmetric matter has yet been found at colliders and considerable efforts went into the derivation of constraints on supersymmetric models. Yet, trying to establish universal bounds is a formidable task given the flexibility of general formulations of supersymmetry. Hence two main avenues have been followed in a complementary manner by the experiments. On one hand, the absence of deviations from Standard Model expectations in various sparticle search channels has been used in a global manner to establish constraints in the parameter space of more restricted theories discussed above, such as the constrained (i.e. complemented by GUT relations) MSSM, mSUGRA, GMSB theories with assumptions on the nature of the LSP and next-to-LSP sparticles,  $\mathcal{R}_p$  versions of the constrained MSSM assuming a single dominant new Yukawa coupling, etc. Coherent and *comprehensive* review articles on the restrictions imposed on specific theories can be found in Ref. [79]. On the other hand, searches for specific sparticles have been used to derive “most conservative” lower

mass limits with the intention of remaining independent from a specific choice of model parameters as far as possible. In a way these constitute “utterly unavoidable constraints”. A review of the most general existing constraints on sparticle masses is provided in Table 8.

The most general and best constraints are obtained at the LEP<sub>II</sub> collider, where remarkably complete analyses of sparticle-pair production have been performed including wide parameter scans carried out in the framework of the MSSM and mSUGRA models with or without  $\tilde{R}_p$  couplings and for GMSB models. These are complemented by LEP<sub>I</sub> results most noticeably in the case of GMSB models when the next-to-lightest sparticle (NLSP) is the  $\tilde{\chi}_1^0$ , and also in the case of coloured sparticles with MSSM or mSUGRA models. The existing constraints on squark masses  $M_{\tilde{q}}$  are summarized in Fig. 9 assuming mass degeneracy for five squark flavours. The stringent constraints on  $M_{\tilde{q}}$  obtained at the Tevatron depend on assumptions on the gluino mass  $M_{\tilde{g}}$ . Existing constraints on the lightest stop mass eigenstate

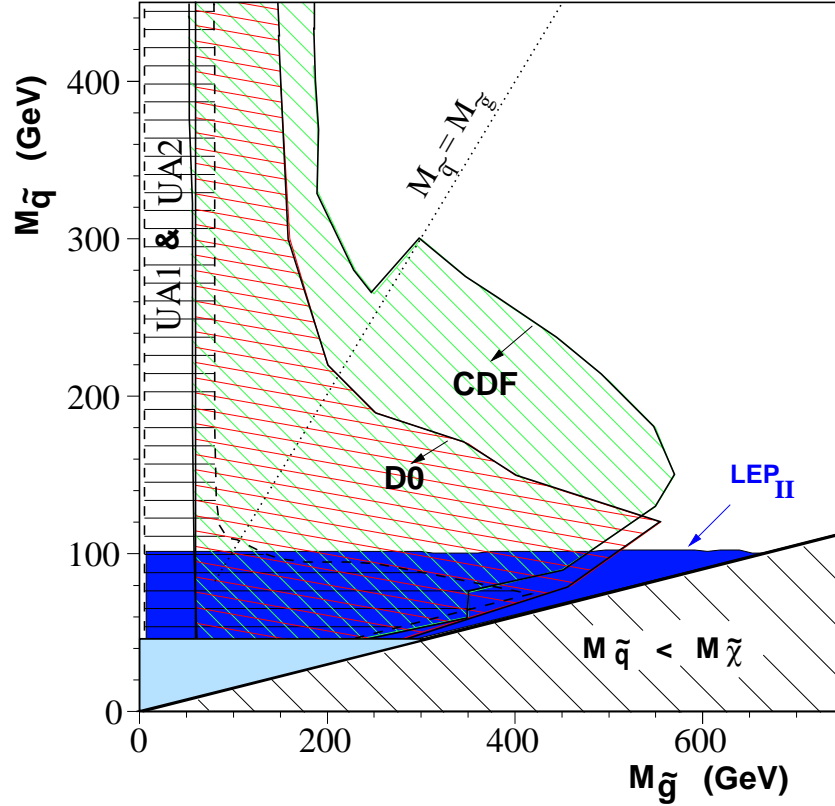


Figure 9: Constraints in the squark mass  $M_{\tilde{q}}$  vs. gluino mass  $M_{\tilde{g}}$  plane derived from a (preliminary) combination [84] of ALEPH, DELPHI, L3 and OPAL results from LEP<sub>II</sub> collider shown together with results obtained [87] by the D0 and CDF experiments at Tevatron<sub>I</sub>.

$\tilde{t}_1$  are summarized in Fig. 10.

For completeness, it should be mentioned that searches for slepton-squark pair production through  $t$ -channel exchange of a  $\tilde{\chi}_1^0$  have been performed by the H1 and ZEUS experiments at HERA [88]. These were sensitive only up to a sum of masses  $M_{\tilde{e}} + M_{\tilde{q}}$  below 150 GeV which is now excluded by LEP<sub>II</sub>-alone “universal” constraints.

Complementary  $\tilde{R}_p$  SUSY searches have been performed at HERA, LEP and Tevatron colliders under

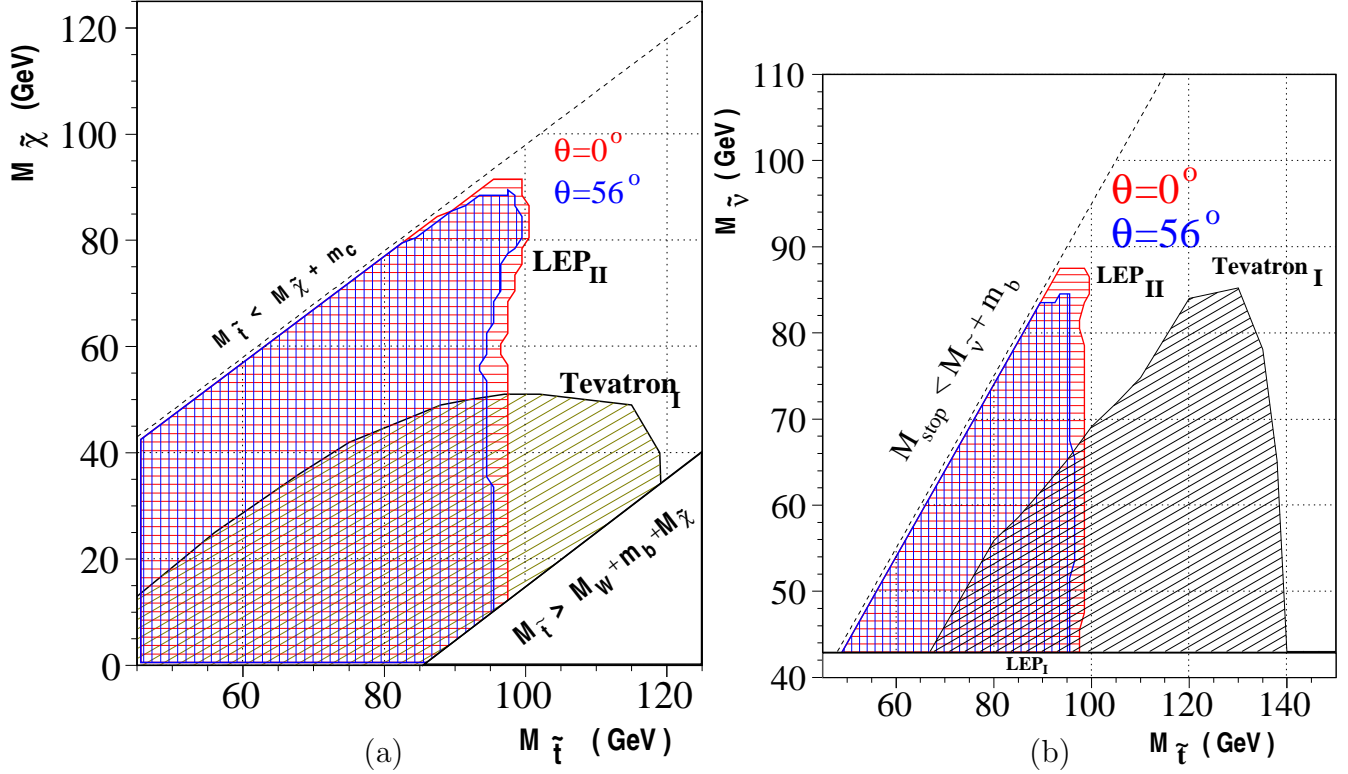


Figure 10: Mass constraints (95% CL) on the stop  $\tilde{t}_1$  eigenstate as a function of the mass of the lightest supersymmetric particle taken either as a) the neutralino  $\tilde{\chi}_1^0$  or b) the sneutrino  $\tilde{\nu}_\tau$ . The excluded domains derived from a (preliminary) combination [84] of ALEPH, DELPHI, L3 and OPAL results from the LEP<sub>II</sub> collider are shown together with results obtained [85] by the DØ and CDF experiments at Tevatron<sub>I</sub>.

the hypothesis of a single dominant  $\lambda'_{ijk}$  coupling. The constraints obtained [89] by the H1 experiment at HERA from a search for resonant squark production via  $\lambda'_{ijk}$  are shown in Fig. 11. Similar results were obtained [90] by the ZEUS experiment. Also shown in Fig. 11 are the best existing indirect bounds [91] from low-energy experiments. The  $\lambda'_{111}$  coupling is seen to be very severely constrained by the non-observation of neutrinoless double-beta decay. The most stringent low-energy constraints on  $\lambda'_{121}$  and  $\lambda'_{131}$  come from atomic-parity violation measurements.

The HERA results analysed in the framework of  $\mathcal{R}_p$  mSUGRA are shown in Fig. 12. The searches were made under the hypothesis of a single dominant  $\lambda'_{ijk}$  coupling and the results are presented as excluded domains in the parameter space of the model.

The constraints from the DØ [95] experiment at the Tevatron were obtained from a search for  $\tilde{q}$  pair production through gauge couplings. The analysis profits from an approximate mass degeneracy implicitly extended to five  $\tilde{q}$  flavours ( $\tilde{d}, \tilde{u}, \tilde{s}, \tilde{c}, \tilde{b}$ ) and both (partners) chiralities ( $\tilde{q}_L, \tilde{q}_R$ ). The  $\mathcal{R}_p$  couplings are assumed to be significantly smaller than the gauge couplings, so that direct  $\mathcal{R}_p$  decays are suppressed and each squark rather decays back into a quark and the LSP through gauge couplings. The only effect of the  $\mathcal{R}_p$  couplings is to make the LSP unstable. The analysis is further restricted to  $\mathcal{R}_p$  coupling values  $\gtrsim 10^{-3}$  to guarantee a negligible decay length of the LSP. In the domains considered, the LSP is almost always the lightest neutralino  $\tilde{\chi}_1^0$ . The  $\tilde{\chi}_1^0$  decays via  $\lambda'_{ijk}$  into a first-generation lepton ( $e$  or  $\nu_e$ ) and

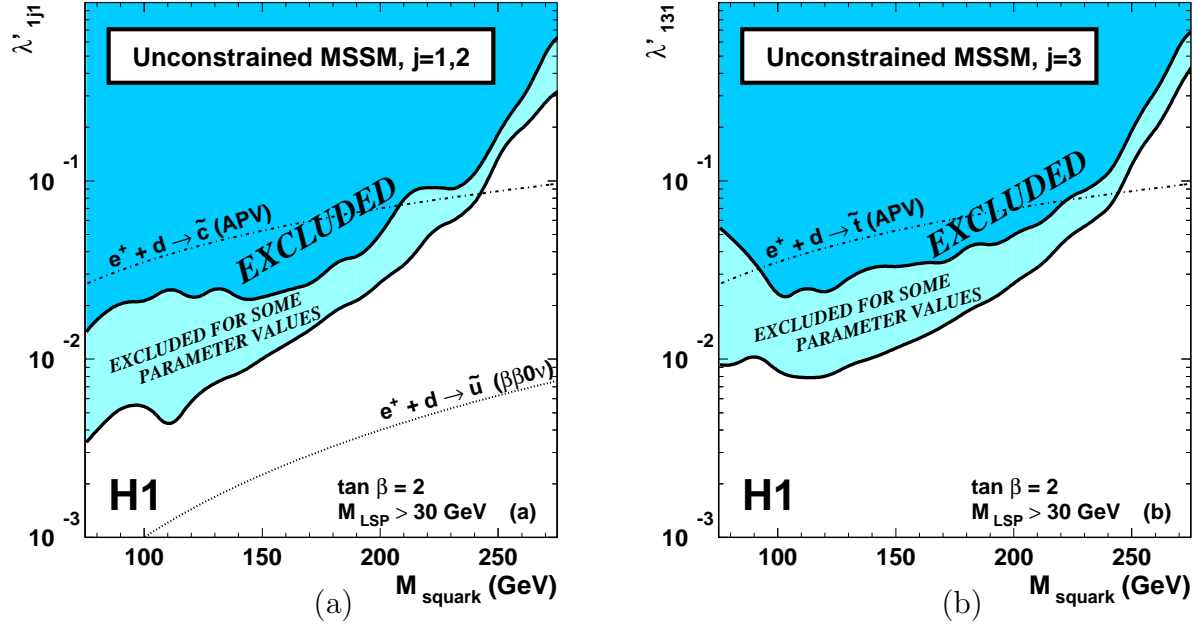


Figure 11: Upper Limits (95% CL) on a) the coupling  $\lambda'_{1j1}$  with  $j = 1, 2$  and b)  $\lambda'_{131}$  as a function of the squark mass for  $\tan \beta = 2$  in the unconstrained MSSM. The limits are obtained from a scan of the  $\mu$  and  $M_2$  parameters within  $-300 < \mu < 300$  GeV and  $70 < M_2 < 350$  GeV and imposing that the lightest sparticle (LSP) has a mass  $M_{LSP}$  above 30 GeV. The dark shaded area is excluded for any parameter values. The light shaded area is excluded for some parameters values. The dotted curve is the indirect upper bound [91] on  $\lambda'_{111}$  derived from constraints on neutrinoless double-beta decays [92, 93]. The dash-dotted curves are the indirect upper bounds [91] on  $\lambda'_{1j1}$  derived from constraints on atomic-parity violation [94].

two quarks. The analysis is restricted to  $j = 1, 2$  and  $k = 1, 2, 3$  and, in practice, the  $D\emptyset$  selection of event candidates requires like-sign di-electrons accompanied by multiple jets.

The constraints from the  $L3$  [96] experiment at LEP were obtained from a search for pair production through gauge couplings of neutralinos ( $e^+e^- \rightarrow \tilde{\chi}_m^0 \tilde{\chi}_n^0$  with  $m = 1, 2$  and  $n = 1, \dots, 4$ ), charginos ( $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ ) and scalar leptons ( $e^+e^- \rightarrow \tilde{l}_R^+ \tilde{l}_R^-, \tilde{\nu} \tilde{\nu}$ ). The  $\mathcal{R}_p$  couplings contribute here again in opening new decay modes for the sparticles. A negligible decay length of the sparticles through these decay modes is ensured by restricting the analysis to coupling values  $\gtrsim 10^{-5}$ . All possible event topologies (multijets and lepton and/or missing energy) resulting from the direct or indirect sparticle decays involving the  $\lambda'_{ijk}$  couplings have been considered in the  $L3$  analysis.

The hatched region marked “not allowed” in Fig. 12 corresponds to points where the radiative electroweak symmetry breaking does not occur; or where the LSP is the sneutrino; or that lead to tachyonic Higgs or sfermion masses.

For the set of mSUGRA parameters with  $\tan \beta = 2$ , the Tevatron experiment excludes squarks with masses  $M_{\tilde{q}} < 243$  GeV (95 % CL) for any value of  $M_{\tilde{g}}$  and a finite value ( $\gtrsim 10^{-3}$ ) of  $\lambda'_{1jk}$  with  $j = 1, 2$  and  $k = 1, 2, 3$ . The sensitivity decreases for the parameter set with a larger value of  $\tan \beta$  due in part to a decrease of the photino component of the LSP, which implies a decrease of the branching fraction



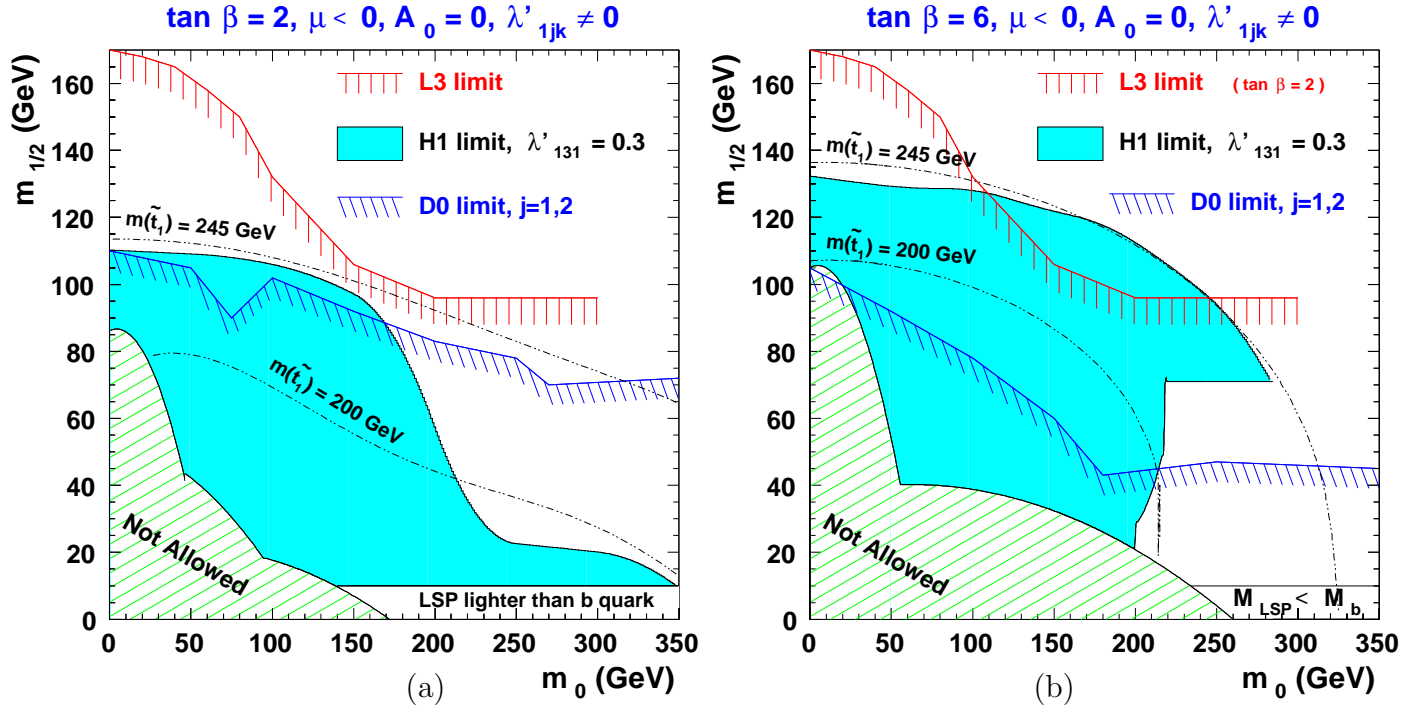


Figure 12: Constraints on stop production via  $\lambda'_{131}$  in  $R$ -parity-violating SUSY in the parameter space of Minimal Supergravity. H1 and D0 limits are shown for a)  $\tan \beta = 2$  and b)  $\tan \beta = 6$ . L3 limit for  $\tan \beta = 2$  is also shown.

of the LSP into electrons, and in part to a softening of the final-state particles for lighter charginos and neutralinos. The best sensitivity at  $\tan \beta = 2$  is offered by LEP for any of the  $\lambda'_{ijk}$  couplings. HERA offers a best complementary sensitivity to the coupling  $\lambda'_{131}$  which allows for resonant stop production via positron-quark fusion  $e^+d \rightarrow \tilde{t}_1$ . The HERA constraints (shown here for a coupling of electromagnetic strength, i.e.  $\lambda'_{131} = 0.3$ ) extend beyond LEP and Tevatron constraints towards larger  $\tan \beta$ .

UTTERLY UNAVOIDABLE CONSTRAINTS ON SPARTICLE MASSES					
Sparticle Type	Model	95% CL $M_{low}$ Limits (in GeV)	Applicability	Experimental Ressources	
<i>Gauginos-Higgsinos (EW sector)</i>					
$\tilde{\chi}_i^0$  $\tilde{\chi}_i^\pm$	MSSM	37	$i = 1; \forall(\tan\beta, m_0)$ ; LSP $\equiv \tilde{\chi}_1^0$ ; GUT rel.	LEP <sub>II</sub> [83]	
	$\mathcal{R}_p$ -SUSY	35-40	LL $\bar{E}$ , $\bar{U}\bar{D}\bar{D}$ ; $\forall$ MSSM	LEP <sub>II</sub> [86]	
		30	LQ $\bar{D}$ ; $\forall$ MSSM	LEP <sub>II</sub> [86]	
	GMSB	77	LSP/NLSP $\equiv \tilde{G}/\tilde{\chi}_1^0$ ; $\beta(\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) = 100\%$	Tevatron <sub>I</sub> [82]	
	MSSM	91	$\tilde{G}$ is LSP, $\tilde{\tau}_1$ is NLSP; $M_{\tilde{G}} < 1$ eV	LEP <sub>II</sub> [80]	
		72	$i = 1; \forall(\tan\beta, m_0)$ ; LSP $\equiv \tilde{\chi}_1^0$ ; GUT rel.	LEP <sub>II</sub> [83]	
		$\mathcal{R}_p$ -SUSY	103	LL $\bar{E}$ , $\bar{U}\bar{D}\bar{D}$ ; $\forall$ MSSM	LEP <sub>II</sub> [86]
			100	LQ $\bar{D}$ ; $\forall$ MSSM	LEP <sub>II</sub> [86]
	GMSB	150	LSP/NLSP $\equiv \tilde{G}/\tilde{\chi}_1^0$ ; $\beta(\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) = 100\%$	Tevatron <sub>I</sub> [82]	
	95		LSP/NLSP $\equiv \tilde{G}/\tilde{\tau}_1$ ; $\forall M_{\tilde{G}}$	LEP <sub>II</sub> [80]	
<i>Gauginos (Strong sector)</i>					
$\tilde{g}$	mSUGRA	190	jets + $\cancel{E}_T$ final states	Tevatron <sub>I</sub> [79]	
		180	dilepton final states	Tevatron <sub>I</sub> [79]	
<i>Sfermions</i>					
$\tilde{e}, \tilde{\mu}, \tilde{\tau}$ $\tilde{e}$ $\tilde{\mu}, \tilde{\tau}$  $\tilde{\nu}$	MSSM	92 / 85 / 68	$\tilde{l}_R$ ; $\Delta M_{\tilde{l}\tilde{\chi}} > 10$ GeV $\tilde{l} \rightarrow l\tilde{\chi}_1^0$ ; $\forall$ mixing	LEP <sub>II</sub> [83]	
	$\mathcal{R}_p$ -SUSY	69-96	LL $\bar{E}$ , LQ $\bar{D}$ , $\bar{U}\bar{D}\bar{D}$ ; $\tilde{l}_R$ pair prod.; $\forall$ MSSM	LEP <sub>II</sub> [86]	
		61-87	LL $\bar{E}$ , LQ $\bar{D}$ , $\bar{U}\bar{D}\bar{D}$ ; $\tilde{l}_R$ pair prod.; $\forall$ MSSM	LEP <sub>II</sub> [86]	
	GMSB	77	$\tilde{\tau}_1$ ; $\tilde{G}$ is LSP, $\tilde{\tau}_1$ is NLSP; $\forall M_{\tilde{G}}$	LEP <sub>II</sub> [81]	
	MSSM	43		LEP <sub>I</sub> [79]	
	$\mathcal{R}_p$ -SUSY	84-99	LL $\bar{E}$ , LQ $\bar{D}$ , $\bar{U}\bar{D}\bar{D}$ ; $\tilde{\nu}_e$ pair prod.; $\forall$ MSSM	LEP <sub>II</sub> [86]	
		64-83	LL $\bar{E}$ , LQ $\bar{D}$ , $\bar{U}\bar{D}\bar{D}$ ; $\tilde{\nu}_{\mu,\tau}$ pair prod.; $\forall$ MSSM	LEP <sub>II</sub> [86]	
	$\tilde{q}$  $\tilde{t}_1$		260	jets + $\cancel{E}_T$ final states	Tevatron <sub>I</sub> [79]
			230	dilepton final states	Tevatron <sub>I</sub> [79]
			90-91	$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0, b\tilde{\nu}$ ; $\Delta M_{\tilde{t}_1\tilde{\chi}} > 7$ GeV; $\forall\theta_{mix}$	LEP <sub>II</sub> [83, 84]
88			$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ ; $M_{\tilde{\chi}_1^0} < 1/2M_{\tilde{t}}$ ; $\forall\theta_{mix}$	Tevatron <sub>II</sub> [79]	
138	$\tilde{t}_1 \rightarrow b\tilde{\nu}$ ; $M_{\tilde{\nu}} < 1/2M_{\tilde{t}}$ ; $\forall\theta_{mix}$	Tevatron <sub>II</sub> [85]			

Table 8: Lower limits at 95% CL on sparticle masses established at LEP and Tevatron colliders.

## 5 Forbidden Lepton and Quark Flavour-Changing Processes

### 5.1 Lepton-Flavour Violation

In the Standard Model, lepton flavours are separately conserved in every reaction. However, the model does not provide a fundamental motivation for this exact additive conservation of electron, muon and tau numbers. It is regarded in the model as resulting from an accidental symmetry.

The observation of lepton-flavour violation (LFV) could provide essential guidance beyond the realm of the Standard Model. This has motivated extensive LFV searches in the charged-lepton sector for the last 30 years in, for instance, largely dedicated experiments using  $\mu$  nuclear capture and rare or forbidden decays of  $\mu$ ,  $\tau$ , or  $K$ ,  $B$  and  $D$  mesons. In the neutrino sector, the strong implication of neutrino mixing to explain recent observations [1] suggests that lepton flavour is violated there. However, a minimal extension of the Standard Model that incorporates neutrino masses and mixings predicts a rate of LFV in the charged-lepton sector far too small to be detected in current and planned experiments. This is due to the smallness of the neutrino masses. On the other hand, many proposed extensions of the Standard Model, for example in GUT theories [2, 97], entail LFV at more fundamental levels and thus predict LFV rates that could be detected in collider experiments and in low-energy processes.

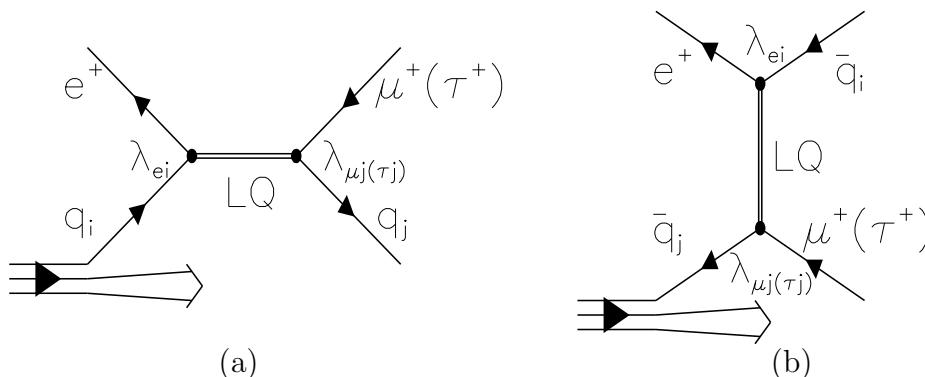


Figure 13:  $ep \rightarrow \mu X(\tau X)$  process mediated by a LFV LQ. a)  $s$ -channel production; b)  $u$ -channel exchange.

Figure 13 shows an example of an LFV process,  $ep \rightarrow \mu(\tau)X$ , which could be observed in  $ep$  collisions. The process is mediated by LQ exchange with couplings involving specific combinations of lepton and quark generations. In Fig. 13, the LQ possesses two non-vanishing Yukawa couplings, a  $\lambda_{ei}$  to an electron and a quark of generation  $i$ , and a  $\lambda_{\mu j(\tau j)}$  to a muon (tau) and a quark of generation  $j$ .

Both the H1 [33] and ZEUS [98] experiments have searched, in  $e^+p$  data taken at  $\sqrt{s} = 300$  GeV, for events with a high-transverse-momentum muon or tau balancing a hadronic jet. ZEUS also reported preliminary search results [99] from  $e^\pm p$  data taken at  $\sqrt{s} = 318$  GeV. No outstanding LQ candidates were found and the null results were interpreted in terms of exclusion limits for two different LQ mass regions described below. The exclusion limits at HERA are derived in a framework that differs from the minimal BRW model introduced in section 2.2 only by a relaxing of the diagonality requirement to allow for combinations of lepton and quark generations. In a similar framework, an exhaustive review of

the contributions of leptoquarks to rare or forbidden lepton and mesons decays and to various precision electroweak tests has been performed by Davidson, Bailey and Campbell [12]. Further discussions concerning contributions to  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow 3e$  and  $\mu - e$  conversion in nuclei can be found in [100].

At HERA, the  $s$ -channel resonant production of leptoquarks dominates for a low-mass assumption,  $M_{LQ} < \sqrt{s}$ . For this case, upper limits on  $\lambda_{\tau j}$  coupling ( $j = 1, 2$ ) are shown in Fig. 14 as a function of a scalar LQ mass for several fixed values of  $\lambda_{e1}$ . The limits cover masses up to 270 GeV and explore a mass-coupling range beyond indirect constraints from rare  $\tau$  decays. The best indirect constraint for  $\lambda_{31}$  comes from the upper limit on the branching ratio  $\beta_{\tau \rightarrow \pi^0 e}$  which could be affected through  $\tau \rightarrow d + LQ^*$ ;  $LQ^* \rightarrow e + d$ . No low-energy process constrains the coupling  $\lambda_{32}$ . More stringent indirect constraints exist for leptoquarks coupling to  $e^+d$  pairs (such as the  $\tilde{S}_{1/2,L}$  in BRW model) for which the couplings  $\lambda_{31}$ ,  $\lambda_{32}$  or  $\lambda_{33}$  are constrained respectively by  $\tau \rightarrow \pi^0 e$ ,  $\tau \rightarrow K^0 e$  and  $B \rightarrow \tau e X$ .

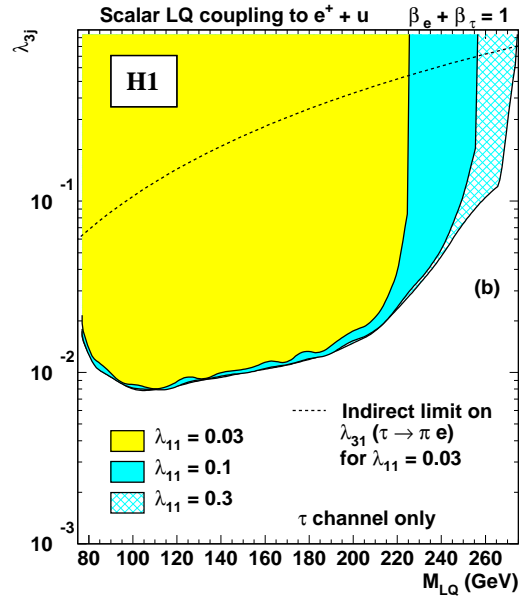


Figure 14: Limits on the leptoquark coupling  $\lambda_{3j}$  (to a  $\tau$  and a quark of generation  $j$ ), for several fixed values of coupling  $\lambda_{11}$  (to an electron and a 1st-generation quark), as a function of the leptoquark mass.

For a high-mass assumption,  $M_{LQ} \gg \sqrt{s}$ , the contributions to  $ep \rightarrow \mu(\tau)X$  from virtual LQ exchanges in the  $s$ - and  $u$ -channels have a cross-section proportional to  $(\lambda_{ei}\lambda_{\mu j(\tau j)}/M_{LQ}^2)^2$ . Note that an initial-state quark that couples to the electron participates in the  $s$ -channel for  $F = 0$  leptoquarks in  $e^+p$  collision, while an initial-state antiquark that couples to the muon or tau must be involved in a  $u$ -channel process, as shown in Fig. 13. For  $F=2$ , the quark and antiquark exchange their roles. Limits derived for high LQ masses [98] are summarized in Table 9 for an  $e \rightarrow \tau$  transition involving any quark-generation combinations and for all  $F = 0$  scalar and vector LQ species. Limits were also obtained [33, 98] at HERA for the  $e \rightarrow \mu$  transition. As can be seen in Table 9, the low-energy limits are quite stringent if first-generation quarks only are involved. However, HERA offers a higher sensitivity for many coupling products involving heavy quarks. For these cases, improved sensitivities from rare  $B$ - and  $\tau$ -decays are expected from  $B$ -factories in the coming years.

A search for LFV processes in  $B^0$ -decays has been performed by the CDF experiment [101] at the

Tevatron. The  $B_d^0 \rightarrow \mu^\pm e^\mp$  and  $B_s^0 \rightarrow \mu^\pm e^\mp$  decays each probe the existence of two types of leptoquarks. For instance, a leptoquark contributing to  $B_s^0 \rightarrow \mu^\pm e^\mp$  *either* couples to  $e - s$  and  $\mu - b$  pairs *or* couples to  $e - b$  and  $\mu - s$  pairs. CDF first establishes the best upper limits on the branching ratios for the decays  $B_d^0 \rightarrow \mu^\pm e^\mp$  ( $\beta < 4.5 \times 10^{-6}$  at 95% CL) and  $B_s^0 \rightarrow \mu^\pm e^\mp$  ( $\beta < 8.2 \times 10^{-6}$  at 95% CL). These results are then interpreted as a lower limit on the mass  $M_V^{PS}$  of Pati-Salam [97] bosons which are vector LFV leptoquarks with non-chiral couplings to quarks and leptons. In such a theory for lepton-quark unification, the leptoquarks couple to fermion pairs with a strong coupling  $\alpha_s(M_{LQ})$ . The CDF limits on the  $B^0$  decays correspond to a lower limit [101] of  $M_V^{PS} > 20$  TeV. A review of the contributions of Pati-Salam leptoquarks to rare or forbidden  $K$ ,  $\pi$  and  $B$  decays can be found in [102].

## 5.2 Flavour-Changing Neutral Currents

In the Standard Model, inter-generation transitions between quarks can happen only via charged currents, i.e. with the  $W$  boson and off-diagonal elements of the Cabibbo-Kobayashi-Maskawa matrix [103]. In contrast, neutral currents are flavour diagonal. Flavour-changing neutral currents (FCNC), i.e. the transition between quarks of the same charge but of different generations, are not contained at tree level and can happen only from higher-order loop contributions. These contributions vanish in the limit of degenerate quark masses (GIM suppression [104]), and therefore, a sizeable (but still very small) rate can arise only when the top quark appears in the loop. This is the case for instance in the FCNC process  $b \rightarrow s\gamma$  which was first observed by the CLEO experiment [105] and has been used to set stringent constraints on physics beyond the Standard Model [68, 106, 107, 108, 109]. In contrast, the GIM suppression is very strong for FCNC decays connecting charge  $+2/3$  quarks because of the relative smallness of the mass of the charge  $-1/3$  quarks involved in the higher-order loops. Therefore, no detectable rate is predicted in the Standard Model for FCNC processes between the top and charm or up quarks; for example, the decay branching ratios  $\beta(t \rightarrow c\gamma, cZ^0)$  are predicted to be  $\sim 10^{-13} - 10^{-12}$ .

However, considerable enhancements are expected for FCNC processes in the top sector [110, 111, 112] in various new models such as models with two or more Higgs doublets, supersymmetric models with or without  $R$ -parity conservation, or models with a composite top quark. Thus, the top-quark phenomenology could be sensitive to physics beyond the Standard Model leading to FCNC processes. Such processes are less tightly constrained in the top sector compared to the lighter quarks and this sector can be tested at current energy-frontier colliders.

In  $e^+e^-$  and  $ep$  collisions, single-top production can be searched for, and in  $pp$  collisions, rare decays of produced top quarks,  $t \rightarrow \gamma q$  and  $t \rightarrow Zq$ , can be used to explore the anomalous top FCNC couplings (Fig. 15).

In the absence of a specific predictive theory, the most general effective Lagrangian was proposed in Ref. [112] to describe FCNC top interactions involving electroweak bosons:

$$\sum_{U=u,c} \left[ \frac{ee_U}{\Lambda} \bar{t} \sigma_{\mu\nu} q^\nu (\kappa_{\gamma,U} - i\tilde{\kappa}_{\gamma,U} \gamma_5) U A^\mu + \frac{g}{2 \cos \theta_W} \bar{t} \{ \gamma_\mu (v_{Z,U} - a_{Z,U} \gamma_5) + i \frac{1}{\Lambda} \sigma_{\mu\nu} q^\nu (\kappa_{Z,U} - i\tilde{\kappa}_{Z,U} \gamma_5) \} U Z^\mu \right]$$

where  $\sigma_{\mu\nu} = (i/2) [\gamma^\mu, \gamma^\nu]$ ,  $\theta_W$  is the Weinberg angle,  $q$  the four-momentum of the exchanged boson,  $e$  and  $g$  denote the gauge couplings relative to  $U(1)$  and  $SU(2)$  symmetries, respectively,  $e_U$  denotes the electric charge of up-type quarks,  $A^\mu$  and  $Z^\mu$  the fields of the photon and  $Z$  boson, and  $\Lambda$  denotes the characteristic mass scale of the new interaction. By convention,  $\Lambda$  is set to  $m_t$ . Only magnetic operators allow FCNC  $tq\gamma$  couplings denoted by  $\kappa_{\gamma,q}$ , while  $q - t$  transitions involving the  $Z$  boson may also occur

via vector (or axial-vector) interactions with  $v_{Z,q}(a_{Z,q})$  coupling due to the non-vanishing  $Z$  mass. The collider results so far have been expressed based on the simplified Lagrangian in Ref. [111], which dealt with only  $\kappa_{\gamma,q}$  and  $v_{Z,q}$  and derived limits<sup>2</sup>  $\kappa_{\gamma,q} < 0.42$  and  $v_{Z,q} < 0.73$  from the CDF experimental results [113] on radiative top decays:  $BR(t \rightarrow q\gamma) < 3.2\%$  and  $BR(t \rightarrow qZ) < 33\%$  at 95% CL.

Electron-proton collisions at HERA are most sensitive to the  $\kappa_{\gamma,u}$  coupling, leading to a  $u$ -quark in the proton changing to a top quark with a  $t$ -channel photon exchange with the electron (see Fig. 15b). The process involving the  $Z$ -boson is much suppressed due to the large mass in the  $t$ -channel propagator. The anomalous coupling to the  $c$ -quark is also suppressed by the small charm density in the proton.

The single-top production at HERA will yield a high-transverse-momentum  $W$  boson accompanied by an energetic hadron jet coming from the other decay product, the  $b$ -quark. When the  $W$  decays leptonically, the event topology will contain an energetic isolated lepton and large missing transverse momentum, as well as large hadronic transverse momentum. For the hadronic decays of  $W$ , the topology will be a three-jet event with a resonant structure in dijet and three-jet invariant masses. Both the H1 [114, 115] and ZEUS [116] collaborations derived limits on  $\kappa_{\gamma,u}$  as shown in Fig. 16. The H1 limits based on leptonic decay channels only [114] are less stringent due to a slight excess of isolated-lepton events observed in the data [117].

The figure also compares limits from LEP [118] and the Tevatron [113, 111]. They are sensitive to both  $\gamma$  and  $Z$  couplings, and both to  $u$ - and  $c$ -quark couplings, since they appear in the final state. Since the LEP centre-of-mass energies are close to the threshold, the dependence on the top-mass uncertainty ( $\delta m \simeq \pm 5\text{GeV}$ ) is sizeable, up to 25% in the coupling limit, while the corresponding HERA uncertainty is about 10% [119].

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<sup>2</sup>These two couplings are often denoted as  $\kappa_\gamma$  and  $\kappa_Z$  in LEP papers.

Table 9: Limits (95% CL upper limit) on  $\lambda_{eq_\alpha}\lambda_{\tau q_\beta}/M_{LQ}^2$  ( $\text{TeV}^{-2}$ ) for  $F=0$  LFV leptoquarks mediating the  $eq_\alpha \leftrightarrow \tau q_\beta$  transition (bold numbers in the bottom of each cell). Each row corresponds to a  $(q_\alpha, q_\beta)$  generation combination and each column corresponds to a leptoquark species. The numbers in the middle of each cell are the best limit from low-energy experiments. The cases where the ZEUS limit is more stringent are enclosed in a box. The \* shows the cases where only the top quark can participate. Similar tables exist for  $F=2$  LQs, and for the  $e\text{-}\mu$  transition. In addition, H1 has similar results.

	$e \rightarrow \tau$		ZEUS		$F = 0$		
$\alpha\beta$	$S_{1/2}^L$ $e^+u_\alpha$	$S_{1/2}^R$ $e^+(u+d)_\alpha$	$\tilde{S}_{1/2}^L$ $e^+d_\alpha$	$V_0^L$ $e^+d_\alpha$	$V_0^R$ $e^+d_\alpha$	$\tilde{V}_0^R$ $e^+u_\alpha$	$V_1^L$ $e^+(\sqrt{2}u+d)_\alpha$
1 1	$\tau \rightarrow \pi e$ 0.4 3.0	$\tau \rightarrow \pi e$ 0.2 2.5	$\tau \rightarrow \pi e$ 0.4 4.6	$G_F$ 0.2 3.3	$\tau \rightarrow \pi e$ 0.2 3.3	$\tau \rightarrow \pi e$ 0.2 2.4	$G_F$ 0.2 1.2
1 2	$\tau \rightarrow \pi e$ 3.1	$\tau \rightarrow Ke$ 5 2.5	$K \rightarrow \pi\nu\bar{\nu}$ $10^{-3}$ 4.7	$\tau \rightarrow Ke$ 3 3.7	$\tau \rightarrow Ke$ 3 3.7	$\tau \rightarrow \pi e$ 2.7	$K \rightarrow \pi\nu\bar{\nu}$ $2.5 \times 10^{-4}$ 1.3
1 3	*	$B \rightarrow \tau\bar{e}X$ 8 5.1	$B \rightarrow \tau\bar{e}X$ 8 5.1	$B \rightarrow l\nu X$ 2 4.6	$B \rightarrow \tau\bar{e}X$ 4 4.6	*	$B \rightarrow l\nu X$ 2 4.6
2 1	$\tau \rightarrow \pi e$ 16	$\tau \rightarrow Ke$ 5 9.2	$K \rightarrow \pi\nu\bar{\nu}$ $10^{-3}$ 12	$\tau \rightarrow Ke$ 3 4.9	$\tau \rightarrow Ke$ 3 4.9	$\tau \rightarrow \pi e$ 6.2	$K \rightarrow \pi\nu\bar{\nu}$ $2.5 \times 10^{-4}$ 2.6
2 2	$\tau \rightarrow ee\bar{e}$ 20 20	$\tau \rightarrow ee\bar{e}$ 30 11	$\tau \rightarrow ee\bar{e}$ 66 12	$\tau \rightarrow ee\bar{e}$ 33 6.2	$\tau \rightarrow ee\bar{e}$ 33 6.2	$\tau \rightarrow ee\bar{e}$ 10 11	$\tau \rightarrow ee\bar{e}$ 6.1 4.3
2 3	*	$B \rightarrow \tau\bar{e}X$ 8 16	$B \rightarrow \tau\bar{e}X$ 8 16	$B \rightarrow l\nu X$ 2 12	$B \rightarrow \tau\bar{e}X$ 4 12	*	$B \rightarrow l\nu X$ 2 12
3 1	*	$B \rightarrow \tau\bar{e}X$ 8 17	$B \rightarrow \tau\bar{e}X$ 8 17	$V_{ub}$ 0.2 5.4	$B \rightarrow \tau\bar{e}X$ 4 5.4	*	$V_{ub}$ 0.2 5.4
3 2	*	$B \rightarrow \tau\bar{e}X$ 8 22	$B \rightarrow \tau\bar{e}X$ 8 22	$B \rightarrow l\nu X$ 2 7.6	$B \rightarrow \tau\bar{e}X$ 4 7.6	*	$B \rightarrow l\nu X$ 2 7.6
3 3	*	$\tau \rightarrow ee\bar{e}$ 30 30	$\tau \rightarrow ee\bar{e}$ 66 30	$\tau \rightarrow ee\bar{e}$ 33 15	$\tau \rightarrow ee\bar{e}$ 33 15	*	$\tau \rightarrow ee\bar{e}$ 6.1 15

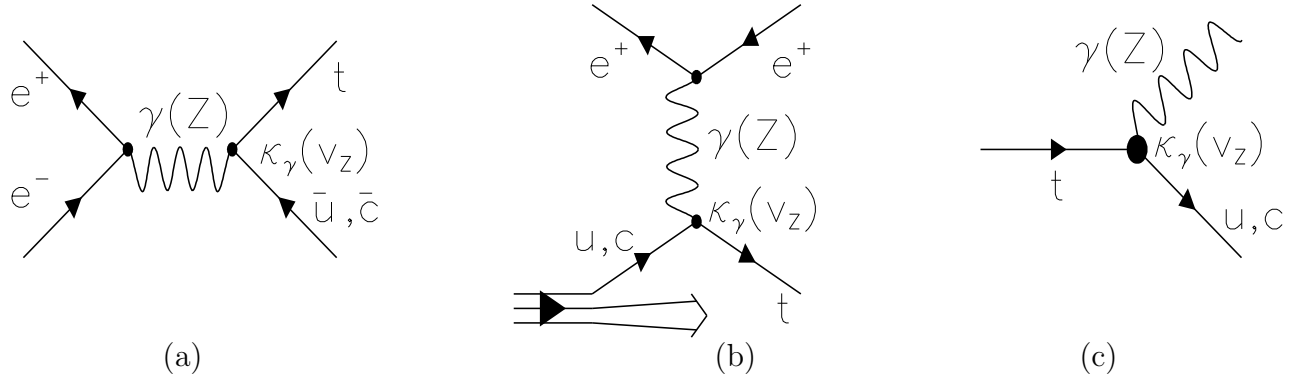


Figure 15: Top FCNC processes at high-energy colliders. a) single-top production in  $e^+e^- \rightarrow tq$ ; b) single-top production in  $ep \rightarrow etX$ ; c) FCNC top decay  $t \rightarrow \gamma(Z)q$ .

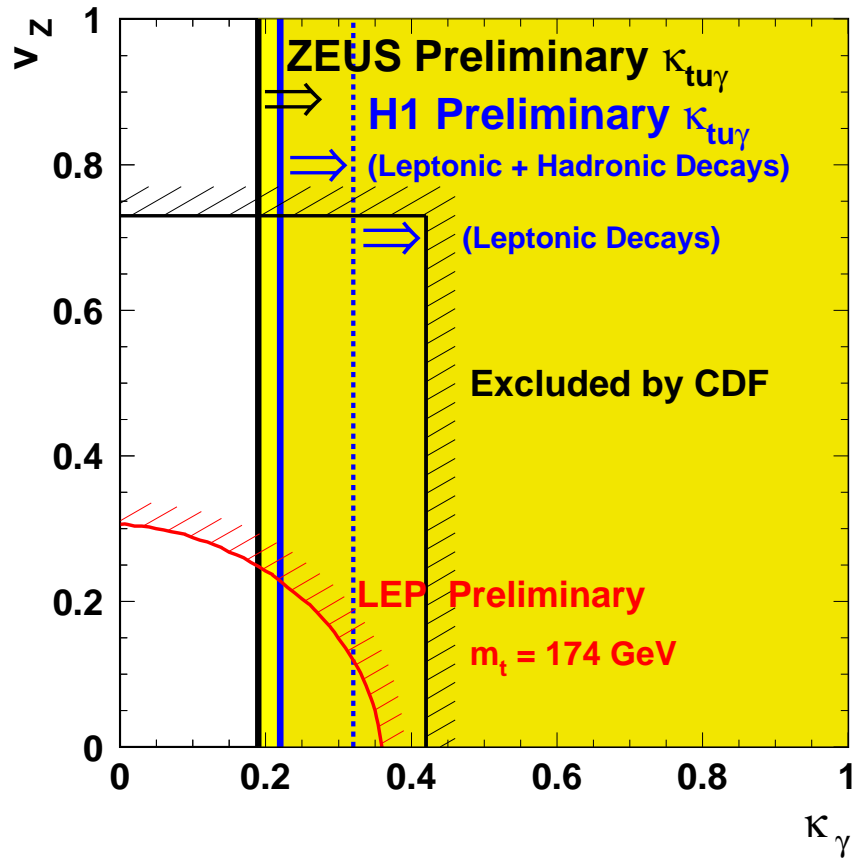


Figure 16: Top FCNC searches at high-energy colliders. For H1 and ZEUS limits, the shaded regions to the right of the vertical lines are excluded. For CDF (LEP), the hatched regions outside the curve (rectangle) are excluded, respectively.



## 6 Extra Bosons and Fermions in Extended Electroweak Models

The symmetries of the Standard Model could be merely the low-energy remains of a more fundamental theory at high energy scales where the strong and electroweak forces would be described by a single Grand Unified (GUT) gauge group. But extensions of the standard electroweak gauge symmetries might also very well be required already at intermediate energy scales, far below GUT unification scales. The new phenomenology expected at colliders for models incorporating such an extension of the electroweak sector is discussed in this section.

Searches and direct constraints on new particles established at colliders as well as the comparison to indirect constraints from low-energy experiments are often discussed in the context of general effective models. An example of such an approach was provided by the Buchmüller-Rückl-Wyler classification and effective Lagrangian of section 2 to study leptoquarks couplings independently of a fundamental theory, i.e. implicitly assuming no other new couplings or new particles beyond the Standard Model. Similar effective approaches have been developed for the search for extra gauge bosons, bileptons or doubly charged particles discussed below. In the absence of an obvious candidate for the true fundamental theory, this seems a pragmatic approach. Now the searches are ultimately motivated by specific (true) fundamental theories, the consequences of which should be ideally discussed as a whole. Among the theories that predict the existence of extra gauge bosons and exotic Higgs scalars and possibly exotic quarks or leptons, are the left-right symmetric models and Standard Model extensions containing triplets of lepton or quark fields. Such models will serve to motivate and guide the searches discussed below, where emphasis is put on extra  $W'$  gauge bosons (subsection 6.1) which come together with heavy right-handed neutrinos in some models, on exotic doubly charged Higgs scalars (subsection 6.2) and on vector gauge bileptons (subsection 6.3) which are associated with exotic quarks in some models.

### 6.1 New Weak Gauge Bosons and Heavy Neutrinos

Extra gauge bosons, often generically denoted as  $Z'$  and  $W'$ , are predicted in left-right symmetric (LRS) models [120, 121, 122, 123] and in other extensions of the Standard Model, such as the  $3 - 3 - 1$  model [124, 125]. They also appear in theories where a strongly interacting sector is responsible for a dynamical electroweak symmetry breaking, as discussed in the effective Lagrangian approach of the BESS model in section 3.2. They are required in the Un-unified Standard Model [126] where quarks and leptons are classified in two distinct  $SU(2)$  gauge groups and, in general, in models with separate  $SU(2)$  gauge factors for each generation [127]. Extra  $Z'$  bosons are furthermore motivated by superstring-inspired models based on the  $E_6$  gauge group which contains  $U(1)$  factors beyond the Standard Model.

In the following we concentrate mainly on  $W'$  and related searches. The existence of new  $W'$  bosons is strongly motivated in particular in LRS models, and will be used here for the discussion. LRS models based on the gauge group  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  provide a simple extension beyond  $SU(2)_L \times U(1)_Y$ . Such models are themselves motivated for example by  $SO(10)$  Grand Unified Theories.

In LRS models, the left-handed fermions transform as doublets under  $SU(2)_L$  and are invariant under  $SU(2)_R$  and *vice versa* for right-handed fermions. The models elegantly restore the symmetry for quarks and leptons to weak interactions. They furthermore provide a natural framework to discuss the origin of parity violation and to understand the smallness of the neutrino mass (via a seesaw mechanism). Supersymmetric LRS models based on the extended electroweak gauge group  $SU(2)_L \times$

$SU(2)_R \times U(1)_{B-L}$  have attracted further attention as they offer the possibility to avoid unwanted  $R$ -parity-violating interactions by gauge symmetries [121, 122, 123]. Such interactions are arguably one of the most problematic features of supersymmetric theories relying on the Standard Model electroweak group and in which trilinear  $\mathcal{R}_p$  interactions are present unless the *ad hoc* assumption of an additional discrete symmetry is invoked. In supersymmetric LRS models, there are no such  $L$ - or  $B$ -violating trilinear interactions admissible [121] in the starting theory <sup>3</sup> and, for instance, the proton becomes automatically protected from fast decays.

As a result of the additional  $SU(2)_R$  symmetry, LRS models predict the existence of three additional gauge-boson fields coupling to right-handed fermions, two charged  $W_R^\pm$  and a neutral  $Z_R^0$ . These appear along with a massive right-handed neutrino  $N_R^i$  for each generation  $i$ . After spontaneous symmetry breaking, the bosons coupling to left- and right-handed fermions mix to form physical mass eigenstates. For the charged bosons  $W_L^- - W_R^-$  (and  $W_L^+ - W_R^+$ ) one has:

$$W_1 = \cos \xi W_L + \sin \xi W_R, \quad W_2 = -\sin \xi W_L + \cos \xi W_R;$$

where  $W_1$  is identified as the known  $W$  boson and  $W_2 \equiv W'$  is a new particle. The expression for the most general Lagrangian that describes the interaction of such bosons with Standard Model fermions can be found in [130]. The Lagrangian contains a phase  $\omega$  reflecting a possible complex mixing parameter in the  $W_L - W_R$  mass matrix, and the  $SU(2)_{L,R}$  gauge couplings  $g_{L,R}$  with  $g_L = g_R$  if parity invariance is imposed.

Reviews of indirect constraints as a function of the free parameters  $\xi$ ,  $g_R/g_L$  and  $M_{W_2}$  can be found in [131, 132, 130]. Taking into account experimental results on  $B - \bar{B}$  mixing,  $b$  decays, neutrinoless double- $\beta$  decays, the  $K_L - K_S$  mass difference, muon decays, etc., a most conservative limit of  $M_{W_R}(g_L/g_R) > 300$  GeV was obtained in Ref. [131] in a model allowing for a non-diagonal mixing matrix  $V^R$  for right-handed quarks and some fine tuning.

Diagrams for the production or exchange of a heavy  $W'$  at colliders are shown in Fig. 17. At  $p\bar{p}$  colliders, the dominant  $W'$  production proceeds via  $\bar{u}d$  ( $W'^-$ ) or  $u\bar{d}$  ( $W'^+$ ) fusion as shown in Fig. 17a. At an  $ep$  collider, the exchange of a right-handed  $W'$  might interfere with standard charged current processes (Fig. 17b for  $M_{\nu_R} \ll M_{W'}$ ) or allow for the production of a heavy and unstable right-handed neutral lepton  $N_R$  (Fig. 17c).

The best direct (but model dependent)  $W'$  constraints have been obtained at hadronic colliders, first by the UA2 experiment [133] at CERN and then by the CDF [134, 135] and DØ [136, 137] experiments at the Tevatron. The searches rely on single  $W'$  production (Fig. 17a) through  $\bar{q}q'$  fusion processes, e.g.  $\bar{u}d \rightarrow W'^-$  or  $\bar{d}u \rightarrow W'^+$ .

Various possible decay modes of the  $W'$ , motivated for instance by LRS models, have been considered separately in the analyses. This includes SM-like leptonic decays  $W' \rightarrow l_R \nu_R$  where the right-handed neutrino is assumed to be light ( $M_{\nu_R} \ll M_{W'}$ ) and escapes detection [134, 136]. Alternatively,  $W'$  is assumed to initiate a decay chain  $W' \rightarrow l_R N_R$ ;  $N_R \rightarrow l \bar{q} q'$  involving a heavy and unstable right-handed neutrino  $N_R$  [136]. For a very heavy  $N_R$  with  $M_{N_R} \gg M_{W'}$ , the analyses rely on hadronic decays  $W' \rightarrow \bar{q} q'$  [135, 137].

In LRS models, and in general in extended gauge models where the new bosons belong to gauge groups different from those of standard bosons, non-vanishing  $W' W Z^0$  couplings only occur through

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<sup>3</sup>Since there are no massless gauge boson in Nature that couples to  $B - L$ , the  $U(1)_{B-L}$  gauge symmetry must be broken. In general,  $L$ -violating (hence  $\mathcal{R}_p$ ) interactions will be induced in the low-energy effective theory through the spontaneous or dynamical breaking of  $U(1)_{B-L}$  by the vacuum [128, 129].

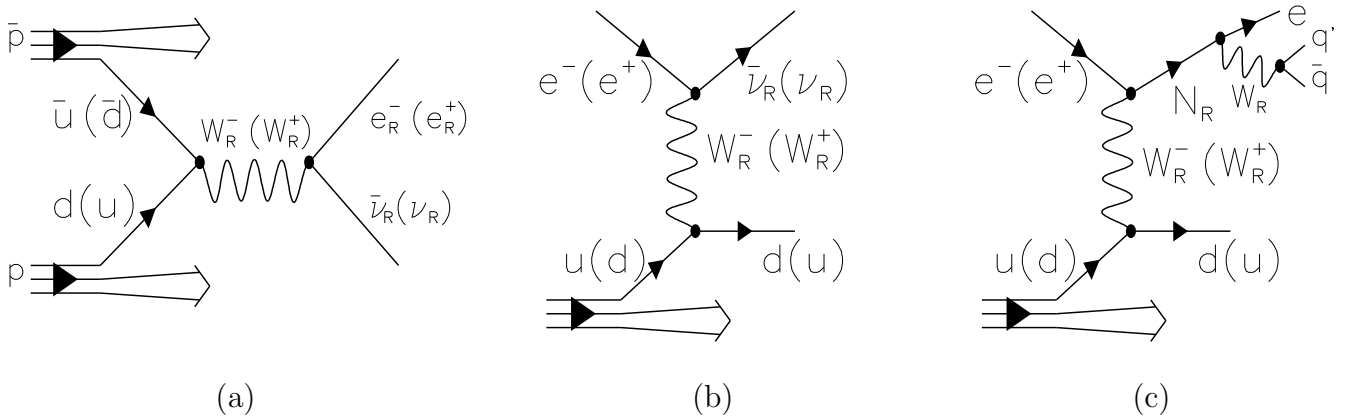


Figure 17: Typical diagrams for  $W'$  production at a)  $p\bar{p}$  and b,c)  $ep$  colliders. a) Single production via  $q\bar{q}$  fusion; b)  $t$ -channel virtual exchange in charged current processes with  $M_{\nu_R} \ll M_{W'}$ ; c)  $t$ -channel virtual exchange with subsequent decay of a heavy Majorana neutral lepton  $N_R$ .

mixing after symmetry breaking. The mixing angles are expected to be small, typically of  $\mathcal{O}(M_W/M_{W'})^2$ , such that the branching ratio for  $W' \rightarrow WZ^0$  is small [138]. However, it has been further argued in Ref. [138] that large branching ratios in that mode are possible in models with a strongly interacting scalar sector or in models with non-linear realization of the electroweak interactions in the limit where the Higgs mass becomes infinite. A search for singly produced  $W'$  decaying into  $WZ^0$  has been recently performed by CDF [139].

Model-dependent assumptions have to be made to translate the experimental observations into  $W'$  constraints. These concern mainly: *i*) the value of the coupling constant  $g_R$  of the  $W'$  to right-handed fermions, which enters in the production cross-section; *ii*) the  $L - R$  mixing angle  $\xi$ , which will determine for instance the relative contribution of  $W' \rightarrow WZ^0$  decays; *iii*) the mass(es) and nature (Dirac or Majorana) of the right-handed neutrinos; *iv*) the values of the elements of the “CKM” mass mixing matrix for right-handed quarks, which also affect the production cross-section.

The  $W'$  mass constraints derived from the Tevatron searches in various (possibly mutually exclusive) decay modes are displayed in Fig. 18. The constraints are given at 95% CL and assuming SM-like coupling values to ordinary fermions and CKM-like values for the mass mixing matrix of right-handed quarks.

The  $W'$  mass is seen to be severely restricted for leptonic decays  $W' \rightarrow l_i \nu'_i$  involving any of the three lepton generations  $i$  and assuming  $M_{\nu'_i} \ll M_{W'}$ . In the limit where  $M_{\nu'_i} \sim 0$ , masses in the range  $[100 < M_{W'} < 754 \text{ GeV}]$  are excluded for  $W' \rightarrow e\nu$  decays,  $[100 < M_{W'} < 660 \text{ GeV}]$  for  $W' \rightarrow \mu\nu$ , and  $[100 < M_{W'} < 610 \text{ GeV}]$  for  $W' \rightarrow \tau\nu$ . For  $M_{\nu'_i} \lesssim M_{W'}/2$ , masses in the range  $[200 < M_{W'} < 650 \text{ GeV}]$  are excluded.

Coupled with the most general indirect constraints for lowish  $M_{W'}$  discussed above, these direct collider constraints seem at first glance to completely exclude a possible signal at the HERA<sub>II</sub>  $ep$  collider.

The sensitivity to new right-handed charged currents at HERA<sub>II</sub> with polarized lepton beams is shown in Fig. 18 assuming parity invariance and for various technical assumptions on the level of lepton-beam polarisation and integrated luminosities. For a precision on the polarisation measurement which

should routinely reach 1.0% and (ambitiously) is aiming for 0.5%, and for an integrated luminosity of  $1 \text{ fb}^{-1}$  shared between opposite helicities,  $W_R$  masses reaching 400 to 500 GeV (depending on the polarisation level) will be probed in charged current processes with  $M_{\nu_R} \ll M_{W'}$ .

In the case of a heavy right-handed neutrino  $N_R$  decaying rapidly inside the detector, a drastic reduction of the Standard Model background (hence an improved discovery reach) becomes possible at HERA by considering the decay  $N_R \rightarrow e\bar{q}q'$ . For  $M_{\nu_R} < M_{W'}$ , this decay involves either a virtual  $W_R$  or, through mixing, a real ordinary  $W$ . Production and decay of Dirac neutrinos will lead only to  $\Delta L = 0$  processes where the charged lepton in the final state carries the same charge as the incident lepton beam. In contrast, both positively and negatively charged leptons would occur with equal rates in the decay of Majorana neutrinos.

The production and decay of Majorana neutrinos at HERA via  $W_L$  has been studied in Ref. [140]. The process involves the boson mixing parameter  $\xi$  and a leptonic mass-mixing matrix  $V_L$ . The total cross-section varies with the square of the strength  $(V\xi)_{eN}$  between the incident  $e_R$  and the produced heavy neutrino  $N_R$ . For  $(V\xi)_{eN} = 0.1$ , the existence of Majorana neutrinos with masses up to  $M_N \simeq 200 \text{ GeV}$  could be probed at HERA<sub>II</sub> for an integrated luminosity of  $1 \text{ fb}^{-1}$ . Irrespective of  $V_L$  and  $\xi$ , Majorana neutrinos could also be produced at HERA via  $W_R$  exchange as in the diagram of Fig. 17c. The sensitivity expected in this channel was studied in the  $M_{W_R}$  vs.  $M_{N_R}$  plane in Ref. [141]. Masses up to  $M_{W_R} = 700 \text{ GeV}$  could be probed for heavy neutrinos with masses up to  $M_{N_R} \simeq 120 \text{ GeV}$ . The mass reach for  $M_{W_R}$  decreases with increasing  $M_{N_R}$  and masses up to only  $M_{W_R} = 450 \text{ GeV}$  could be probed for  $M_{N_R} \simeq 180 \text{ GeV}$ . Thus, the mass reach at HERA<sub>II</sub> for right-handed currents accompanied by the production of a heavy Majorana neutrino decaying via  $N_R \rightarrow e\bar{q}q'$  appears to be already well covered by Tevatron<sub>I</sub> searches.

The stringent collider constraints on  $M_{W'}$  from leptonic decays can be partly evaded if  $M_{N_R} \gg M_{W'}$  but then masses in the range  $[300 < M_{W'} < 420 \text{ GeV}]$  are nevertheless excluded via the  $W' \rightarrow \bar{q}q'$  channel. If this in turn is turned off because  $W' \rightarrow WZ^0$  decays dominate, then masses in the range  $[200 < M_{W'} < 480 \text{ GeV}]$  remain excluded.

A way to partly evade  $p\bar{p}$  collider constraints while possibly preserving the sensitivity of charged current processes at an  $ep$  collider consists of allowing for a non-standard quark mass-mixing matrix in the right-handed sector [142]. As an illustration of an extreme case, one can consider for example a mixing matrix with  $V_{us}^R = 1$  (thus with  $V_{ud}^R = 0$  for a unitary  $V^R$ ). This leads to a suppression of the production in  $p\bar{p}$  collisions, which depends dominantly on a product of the  $u$  and  $d$  valence-quark densities in the proton. In contrast, the  $W'^+$  exchanged with a valence quark in an  $e^+p$  interaction or the  $W'^-$  exchanged in an  $e^-p$  interaction can only couple respectively to the  $d$  or  $u$  quark. The  $W'^-$  contribution to charged currents in  $e^-p$  collisions would thus remain largely unaffected in this extreme case. Such an extreme case was considered in a  $D\bar{0}$  analysis [136] which excludes masses in the range  $[200 < M_{W'} < 380 \text{ GeV}]$  for  $V_{us}^R = 1$  and  $g_R/g_L = 0.55$ . This is labelled as a “worse-case scenario” for  $p\bar{p}$  colliders in Fig. 18. It helps in emphasizing the necessity for extremely good precision  $\delta P$  on the lepton-beam polarisation at the  $ep$  collider.

For completeness, and although it appears to be very difficult if not impossible to avoid the  $M_{W_R} > 300 \text{ GeV}$  constraints from precision measurements and rare or forbidden decays [131], it should be remarked that none of the existing direct searches carried out at CERN or Tevatron covered the range  $M_{W_R} \lesssim 100 \text{ GeV}$ . This is even more so in the case where  $M_{N_R} > M_{W_R}$  if the  $W_R$  decays only via  $W_R \rightarrow \bar{q}q'$ . In that case a “hole” has been left between the di-jet coverage of the UA2 experiment, which reaches  $M_{W_R} \simeq 250 \text{ GeV}$ , and the range covered by the CDF analysis which starts at  $M_{W_R} \simeq 300 \text{ GeV}$ .

The sensitivity at HERA to heavy Majorana neutrinos in the case  $M_{W_R} \lesssim 100$  GeV and  $M_{N_R} > M_{W_R}$  was discussed in Ref. [143] and a preliminary analysis made by ZEUS showed [144] for an integrated luminosity of about  $10 \text{ pb}^{-1}$  that only  $M_{N_R}$  values below the top quark mass could be probed at HERA for  $g_R = g_L$  and  $W_R$  masses up to the common  $W$  mass.

## 6.2 Doubly Charged Higgs Scalars

We have discussed in subsection 6.1 the case of the additional gauge bosons predicted by LRS models. Here we would like to focus on a possible consequence of the extension of the Higgs sector required by such models, namely the prediction of doubly charged Higgs physical states [120, 145, 146]. Doubly charged Higgs bosons are also present in other scenarios [147, 148, 149, 150, 151] containing triplet Higgs fields but not necessarily incorporating left-right symmetry.

In most LRS models, new additional triplets of Higgs scalar bosons are introduced which act solely in the leptonic sector [152, 153, 154]. Two different Higgs multiplets are needed to preserve the left-right symmetry. They connect to either left- or right-handed lepton chiral states. The so-called “right-handed” Higgs field is responsible for  $SU(2)_R$  symmetry breaking and gives the heavy mass to the right-handed Majorana neutrinos needed in the seesaw mechanism. As a general feature of LRS models [120, 145, 146], the Higgs multiplets contain doubly charged elements, leading to the existence of two physical doubly charged Higgs particles, labelled  $\Delta_L^{--}$  and  $\Delta_R^{--}$ . Actually, it has been shown on very general grounds that large classes of supersymmetric LRS models do necessarily [129] contain such doubly charged Higgs fields and that the physical states tend to be very light [155, 129]. This remains true whether or not the  $SU(2)_R$  weak scale is in the superheavy range and holds even when  $R$ -parity gets spontaneously broken [129]. The doubly charged Higgs bosons are members of the so-called “left-” and “right-handed” triplets  $(\Delta^0, \Delta^-, \Delta^{--})_{L,R}$  and carry the quantum number  $|B - L| = 2$ .

The doubly charged Higgs boson could in principle couple to ordinary EW bosons and/or to other Higgs bosons but, in a likely scenario, the couplings to lepton pairs could determine the relevant phenomenology. Indeed, trilinear  $\Delta L = 2$  couplings of the type  $WW\Delta^{--}$  which could allow for single production via  $t$ -channel  $WW$  fusion are not necessarily present in the theory [151, 153]. For the  $W_L W_L \Delta_L^{--}$ , the coupling must be in any case vanishingly small given the constraints set by the electroweak  $\rho$  parameter which involves the mass ratio of ordinary weak bosons [156]. For the  $W_R W_R \Delta_R^{--}$ , the coupling strength depends on the scale of the left-right symmetry breaking and will be suppressed for a very heavy  $W_R$  [157]. Moreover, in particular in the framework of supersymmetric LRS models, the decay  $\Delta_R^{--} \rightarrow W_R^- W_R^-$  of a real doubly charged Higgs boson might very well be closed because of a heavy or superheavy  $W_R$ . In addition, bosonic decays of the type  $\Delta^{--} \rightarrow \Delta^- W_R^-$  or  $\Delta^{--} \rightarrow \Delta^- \Delta^-$  are possible but also likely to be disallowed. Finally, given that the doubly charged Higgs boson cannot couple to quark pairs because of charge conservation, a real doubly charged Higgs boson may very well be left with only like-sign lepton-pair decays. Of course, couplings to the  $\gamma$  and  $Z^0$  are always present.

Since the  $\Delta_L$  and  $\Delta_R$  triplets are not involved in the mass-generation mechanism for the ordinary charged leptons, the doubly charged Higgs boson couples to ordinary charged leptons independently of their mass ! Hence, there are no mass-suppression effects for light leptons and the decay branching ratio into like-sign charged leptons of each of the three generations could be in principle similar. In detail the couplings  $k_L^i$  of the  $\Delta_L^{--}$  are arbitrary and can be treated as free parameters. The couplings  $k_R^i$  of the  $\Delta_R^{--}$  are proportional to the mass  $M(N^i)$  of the new heavy right-handed Majorana neutrinos which are introduced for each generation  $i$ . These could be almost degenerate but not necessarily so.

While heavy Majorana neutrinos could be beyond the reach of colliders, the  $\Delta_R^{--}$  could still retain a large coupling to like-sign lepton pairs. The relative  $k^i$  values will fix the (unknown) relative branching ratio into like-sign lepton pairs of a given generation.

A very important property of the doubly charged Higgs boson when considering indirect constraints [158] is that they naturally avoid some of the most sensitive tests of lepton-flavour conservation. The reason is that such tests often involve initial-state hadrons where they can only contribute as higher-order corrections. The indirect constraints can be parametrized in terms of the mass  $M_{\Delta^{--}}$  of the scalar and a coupling constant  $h_{ij}$  where  $i, j = e, \mu, \tau$ . They have been discussed in Refs. [158, 159, 160, 161].

The off-diagonal products  $h_{ij}h_{i'j'}$  with either  $i \neq j$  or  $i' \neq j'$  suffer from stringent constraints for the first- and second-generation charged leptons from forbidden  $\mu \rightarrow e^+e^-e^-$  and  $\mu \rightarrow e\gamma$  decays [161]. Assuming that only purely diagonal couplings are non-vanishing, the existing constraints are remarkably mild. Constraints involving  $h_{ee}$  come from a possible virtual  $\Delta^{--}$  exchange contribution to Bhabha scattering in  $e^+e^-$  collisions (see below) which yields [158, 161]

$$h_{ee}^2 \lesssim 9.7 \times 10^{-6} \text{ GeV}^{-2} M_{\Delta^{--}}^2$$

and from the search for muonium ( $\mu^+e^-$ ) to anti-muonium ( $\mu^-e^+$ ) conversion which yields

$$h_{ee}h_{\mu\mu} \lesssim 5.8 \times 10^{-5} \text{ GeV}^{-2} M_{\Delta^{--}}^2.$$

For the coupling  $h_{\mu\mu}$  alone, avoiding possible extra contribution to  $(g-2)_\mu$  yields

$$h_{\mu\mu}^2 \lesssim 2.5 \times 10^{-5} \text{ GeV}^{-2} M_{\Delta^{--}}^2.$$

No stringent constraints involving the  $\tau$  lepton have been established.

At  $e^+e^-$  colliders the  $\Delta^{--}$  scalars can be pair produced through their  $Z\Delta^{++}\Delta^{--}$  or  $\gamma\Delta^{++}\Delta^{--}$  couplings (see Fig. 19a). Pair production can also proceed through  $u$ -channel exchange (Fig. 19b) involving only couplings to electron-positron pairs. For pair production, the kinematic reach is of course restricted to  $M_{\Delta^{\pm\pm}} < \sqrt{s_{ee}}/2$ . The  $\Delta^{\pm\pm}$  can be exchanged in the  $t$ -channel (Fig. 19c), thus providing an anomalous contribution to “Bhabha” scattering. Finally, single production is possible via diagrams involving a  $\gamma^*e \rightarrow \Delta^{\pm\pm}e$  sub-process as seen for example in Fig. 19d. The relevant phenomenology has been discussed in Refs. [152, 160, 162, 163]. Single production of doubly charged Higgs bosons in  $\gamma e$  collisions at linear colliders has been discussed in Refs. [164, 161, 165]. Resonant production in  $e^-e^-$  collisions has been discussed in Ref. [151]. The case for future  $\gamma\gamma$  colliders has been discussed in Ref. [166].

At the Tevatron  $p\bar{p}$  collider, a doubly charged Higgs boson could be pair produced via its coupling to  $\gamma/Z^0$  electroweak bosons in the reactions  $p\bar{p} \rightarrow \gamma/Z^0 X \rightarrow \Delta^{--}\Delta^{++} X$  (see Fig. 20a). Such production reaching larger  $\Delta^{\pm\pm}$  masses will be possible at a  $pp$  collider like the LHC, where it requires an anti-quark carrying a large momentum fraction of the proton. Single production via  $WW$  fusion at hadronic colliders could very well be suppressed by vanishingly small trilinear couplings. The relevant phenomenology has been discussed in Refs. [159, 162, 153, 157, 163, 167, 156].

With a production cross-section estimated [162] to be below  $\mathcal{O}(10^{-2})$  pb for  $\Delta^{\pm\pm}$  masses above 45 GeV, the mass reach for pair production via photon-photon fusion at the HERA  $ep$  collider is completely covered by LEP. On the other hand, HERA allows for single production of doubly charged scalars through the  $h_{ee}$  coupling for example by the fusion of the incoming electron with an electron provided by a photon radiated from the proton (see Fig. 20b), or in “leptonic radiative return” processes

(Fig. 20c). The phenomenology for HERA has been discussed in Ref. [168] but considering only elastic production, and thus neglecting possibly equally important contributions from quasi-elastic and inelastic processes. HERA is found to offer an almost background-free search environment in the reactions  $e^-p \rightarrow e^+p\Delta^{--}$  followed by the decays  $\Delta^{--} \rightarrow e^-e^-; (\mu^-\mu^-, \tau^-\tau^-)$  or for non-diagonal couplings  $e^-p \rightarrow \mu^+p\Delta^{--}$  followed by the decays  $\Delta^{--} \rightarrow e^-\mu^-; (e^-\tau^-, \mu^-\tau^-)$ . A most promising signal at high masses would be three leptons with two of them of the same sign at large invariant mass values.

A summary of existing direct and indirect constraints on the doubly charged Higgs boson is shown in Fig. 21 in the case of the  $h_{ee}$  coupling as a function of its mass. Masses  $M_{\Delta^{\pm\pm}} \lesssim 45.6$  GeV have been excluded by the OPAL experiment analyzing  $Z^0$  decays at LEP<sub>I</sub> [169]. As seen on Fig. 21, this was extended by OPAL to  $M_{\Delta^{\pm\pm}} \lesssim 98.5$  GeV (95% CL) in a search [170] for pair production in the  $s$ -channel using LEP<sub>II</sub> data at centre-of-mass energies between 189 GeV and 209 GeV. Similar results were derived by OPAL for any relative values of the  $h_{ee}$ ,  $h_{\mu\mu}$  and  $h_{\tau\tau}$  couplings, assuming a 100% decay branching fraction into charged-lepton pairs. A similar lower limit on  $M_{\Delta^{\pm\pm}}$  has been obtained recently by the DELPHI experiment at LEP<sub>II</sub> [171] in the  $\Delta^{\pm\pm} \rightarrow \tau^\pm\tau^\pm$  channel. A search for single production of doubly charged Higgs bosons [172] has been performed very recently by OPAL which also considered indirect effects on measurements of Bhabha scattering at LEP<sub>II</sub>. The resulting constraints are shown in Fig. 21.

The constraints obtained at HERA<sub>I</sub> by the H1 experiment [173] are also shown on Fig. 21 together with an estimation of the prospects for HERA<sub>II</sub>. For a coupling of electromagnetic strength,  $h_{ee} = e$  with  $e \equiv \sqrt{4\pi\alpha}$ , doubly charged Higgs bosons which would decay with 100% branching into like-sign and like-flavour charged leptons have been probed at HERA<sub>I</sub> for masses  $M_{\Delta} \gtrsim 130$  GeV. The sensitivity at HERA<sub>II</sub> will be competitive with the one of LEP<sub>II</sub>, extending the mass reach to  $M_{\Delta} \gtrsim 200$  GeV.

## 6.3 Bileptons

The doubly charged Higgs scalars discussed above can also be seen as a special kind of particle (the scalars) among those coupling to like-sign lepton pairs and generically called “bileptons”. Another kind of bileptons that have received considerable attention in the literature are vector bileptons<sup>4</sup>.

Vector bileptons originally appeared in extensions of the Standard Model such as the “lepton-triplet theories” [175] and in GUT theories such as  $SU(15)$  [17]. But most of the recent discussions have focused on a chiral theory where the three fermion generations and family structure of the Standard Model is embedded in a  $SU(3)_C \times SU(3)_L \times U(1)_Y$  gauge group [124, 125]. The symmetries of this  $3 - 3 - 1$  group are assumed to break down to those of the Standard Model at low energies. This spontaneous breaking requires the existence of four new massive gauge vector bosons carrying lepton number  $L = \pm 2$  and an additional neutral gauge boson  $Z'$  [124]. The bileptons appear in doublets formed of doubly charged and singly charged members ( $X^{\pm\pm}, X^\pm$ ).

At high energies, the particle content in the leptonic sector is exactly the same as in the Standard Model but there is a symmetry among the  $l_i^-$ ,  $l_i^+$ , and  $\nu_i$  of each generation  $i$ , and these come in triplets of  $SU(3)_L$ . The quark sector is more complex and the quark content must be enlarged beyond ordinary

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<sup>4</sup>There is currently no agreed convention in the literature for the usage of the name “bilepton”. In a recent general classification [174], the name has been used to designate any bosons coupling to pairs of leptons including e.g. electroweak bosons carrying lepton number  $L = 0$ . Here we rather reserve the name to scalar or vector bosons carrying  $|L| = 2$ . Some authors have used the nomenclature “bilepton” or “dilepton” to designate more specifically vector bosons carrying  $|L| = 2$ .

quarks. In particular, at least one of the quark generation must be treated differently from the other two. As a generic feature, models containing doubly charged bileptons require the existence of one exotic quark of electric charge  $Q_{em} = +5/3$  in either one of the generations and two  $Q_{em} = -4/3$  quarks [175, 124, 176, 177, 125] in the other two generations. This special treatment of the quarkonic sector is required to ensure anomaly cancellation for exactly three fermion generations. Turning the argument around, it has been seen as a virtue of such models (in contrast to the Standard Model) that the number of fermion generations, which is related to the number of quark colours through the requirement of anomaly cancellation, is thus “predicted” to be exactly three.

A comprehensive review of existing indirect constraints on bileptons has been recently performed [174] in a general approach considering the Lagrangian for all possible bilepton-lepton-lepton couplings consistent with electroweak symmetries. The allowed bilepton states in such an approach are listed in Table 10.

L =2 Bileptons					
Type	Spin	$T_3$	$Q_{em}$	Coupling to	siblings
$L_1$	0	0	1	$l_L \nu_L$	
$\tilde{L}_1$	0	0	2	$l_R l_R$	
$L_2^\mu$	1	-1/2	1	$e_R \nu_L$	$(X^-, X^{--})$ doublet in 3-3-1 models
		+1/2	2	$e_R e_L$	
$L_3$	0	-1	0	$\nu_L \nu_L$	“Left-handed” $(\Delta^0, \Delta^-, \Delta^{--})$ Higgs triplet in Left-Right symmetric models
		0	1	$e_L \nu_L$	
		+1	2	$e_L e_L$	

Table 10: Bileptons with leptonic number  $|L| = 2$  in the Cuypers-Davidson effective model [174] from a most general lepton-number conserving and renormalisable Lagrangian consistent with  $SU(2)_L \times U(1)_Y$  symmetries. The bileptons are grouped in isospin families. The allowed states can be distinguished by their spin, the third component  $T_3$  of their weak isospin, and their electric charge  $Q_{em}$ . The bilepton-lepton-lepton couplings are left as free parameters in the model. The coupling matrix for the  $L_1$  isosinglet is by construction antisymmetric in flavour space while those of the  $\tilde{L}_1$  isosinglet and  $L_3$  isotriplet are symmetric. The isodoublet  $L_2^\mu$  is left with an arbitrary  $3 \times 3$  coupling matrix.

The phenomenology aspects of vector-bilepton production has been studied in the literature for  $e^+e^-$  [16, 178],  $p\bar{p}$  [179] and  $ep$  [180, 181] colliders. As in the case of doubly charged Higgs scalar bosons, the doubly charged vector bileptons  $X^{\pm\pm}$  could be a source of spectacular multi-lepton events. A diagram for single production of a doubly charged  $X^{--}$  at an  $ep$  collider is shown in Fig. 22a. The production of a singly charged bilepton at the  $ep$  collider could also lead in principle to striking event topologies as seen in Fig. 22b. In case real production of a dilepton would turn out to be inaccessible at the HERA<sub>II</sub> collider, striking event topologies could still be expected from a  $t$ -channel exchange of a doubly charged bilepton leading to the creation of an exotic quark as shown in Fig. 22c. In 3-3-1 models containing an exotic quark with  $Q_{em} = -4/3$  in the first generation [124], the dominating process would be  $e^-p \rightarrow e^+X$  via the exchange of a  $X^{--}$ . In contrast, 3-3-1 models containing the exotic quark with  $Q_{em} = 5/3$  in the first generation [177] prefer  $e^+p \rightarrow e^-X$  via the exchange of a  $X^{++}$ . Such processes have been studied in Refs. [182, 181]. Sizeable cross-sections are expected at HERA<sub>II</sub> for the exchange



of doubly charged bileptons with masses from  $\simeq 200$  up to 1000 GeV associated with exotic quarks with masses below  $\simeq 200$  down to 100 GeV, respectively.

Having dared to contemplate the possibility of creating exotic quarks at  $ep$  colliders in processes involving the virtual exchange of bileptons, it is only fair to mention that the possible existence of exotic quarks and leptons is a subject by itself which has been thoroughly reviewed recently in a very general context [183]. Direct searches for a fourth-generation quark of charge  $Q_{em} = -1/3$  have been performed by the DØ and CDF experiments at the Tevatron [184] with a sensitivity to masses reaching  $\sim 200$  GeV.

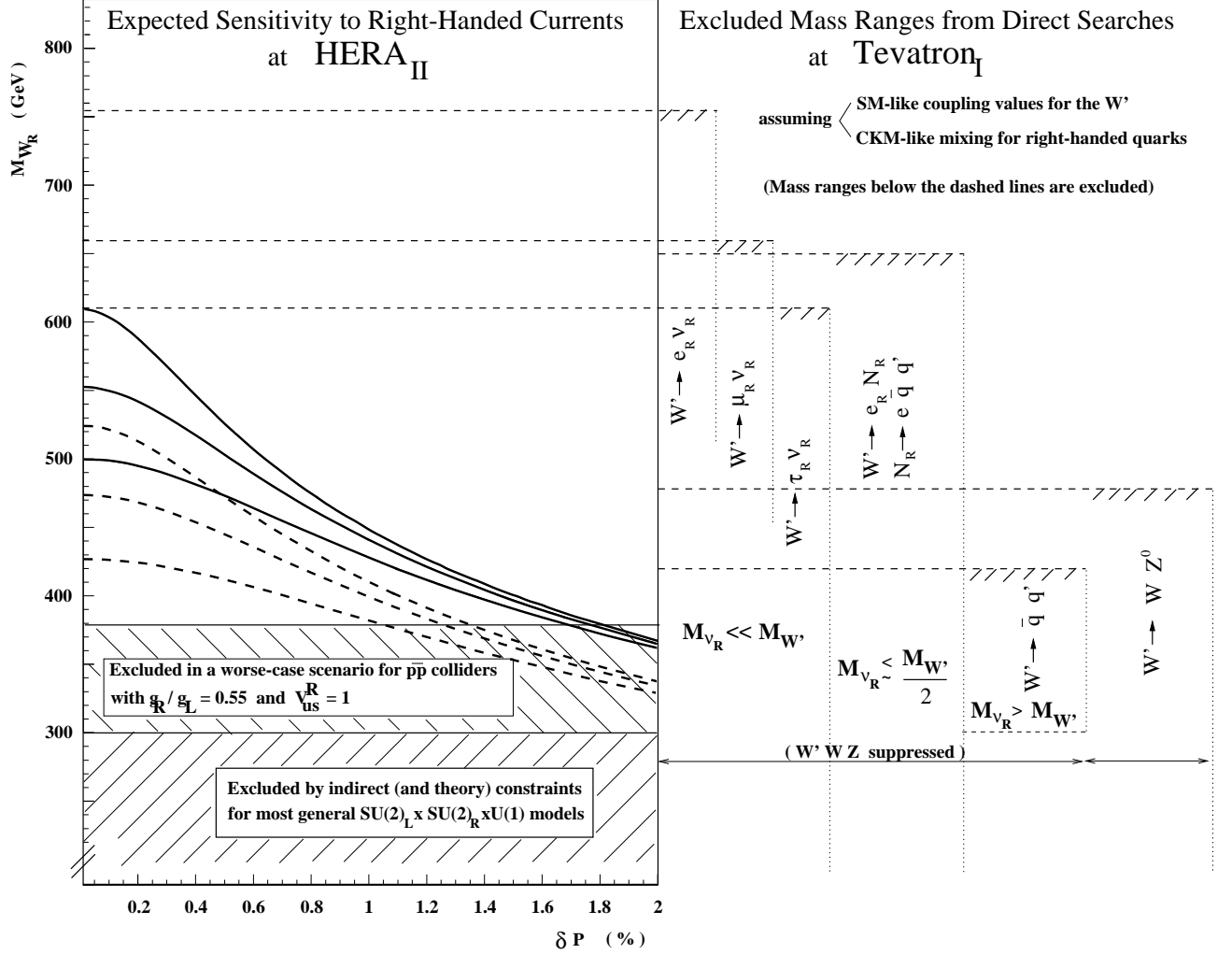


Figure 18: Direct and indirect constraints on a new heavy right-handed boson  $W_R$ . The hatched domain at  $M_{W_R}(g_L/g_R) < 300$  GeV is excluded by a most conservative model taking into account indirect measurements [131]. The curves represent the expected exclusion lower limits (95 % CL) obtainable at HERA<sub>II</sub> by total cross-section measurements as a function of the precision  $\delta P$  on the lepton-beam polarisation for a polarisation level of  $P = 70\%$  (solid) and  $P = 50\%$  (dashed), and for integrated luminosities of  $0.5 \text{ fb}^{-1}$  (lower),  $1 \text{ fb}^{-1}$  (middle) and  $2 \text{ fb}^{-1}$  (upper). Model-dependant lower limits from direct searches at hadronic colliders are also shown.

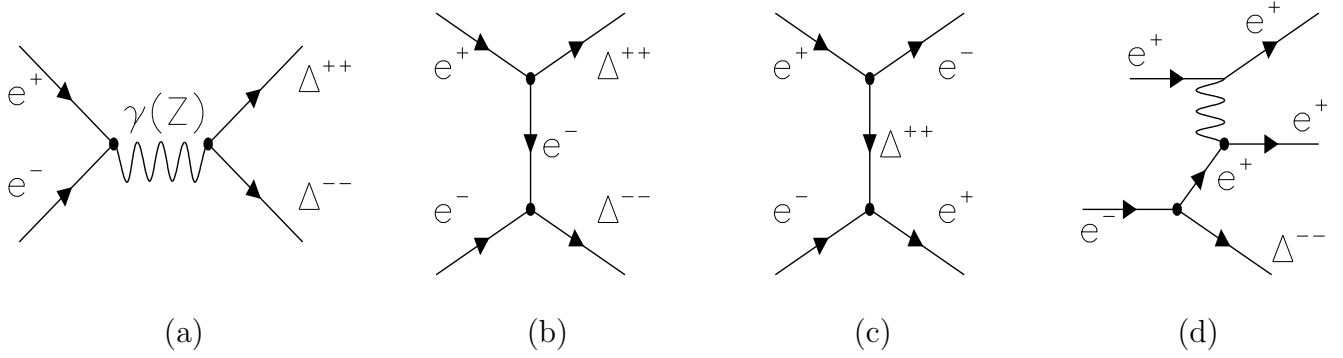


Figure 19: Typical diagrams for doubly charged Higgs boson production at  $e^+e^-$  colliders. a)  $s$ -channel pair production; b)  $u$ -channel pair production; c)  $t$ -channel virtual exchange; d) single production.

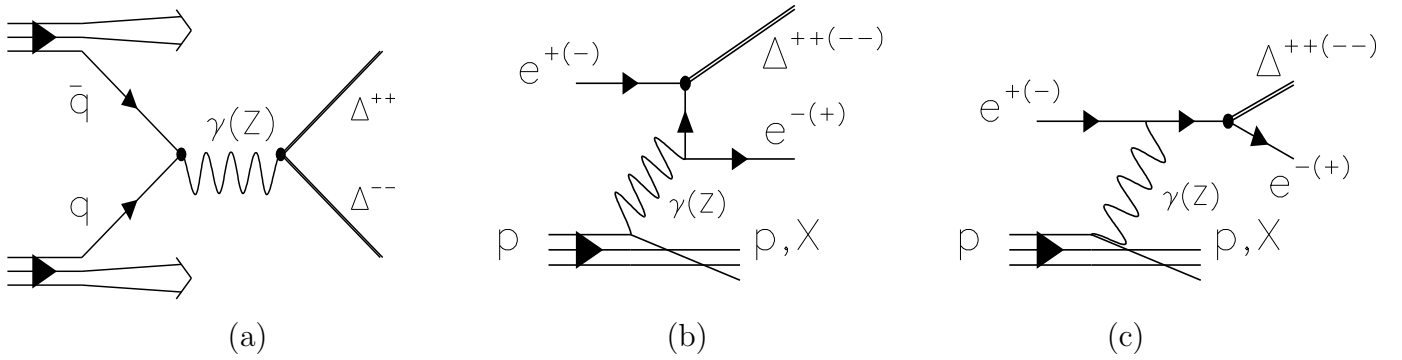


Figure 20: Typical diagrams for doubly charged Higgs boson production at hadronic and lepton-hadron colliders. a) pair production in  $p\bar{p}$  collisions; b,c) single production in  $ep$  collisions.

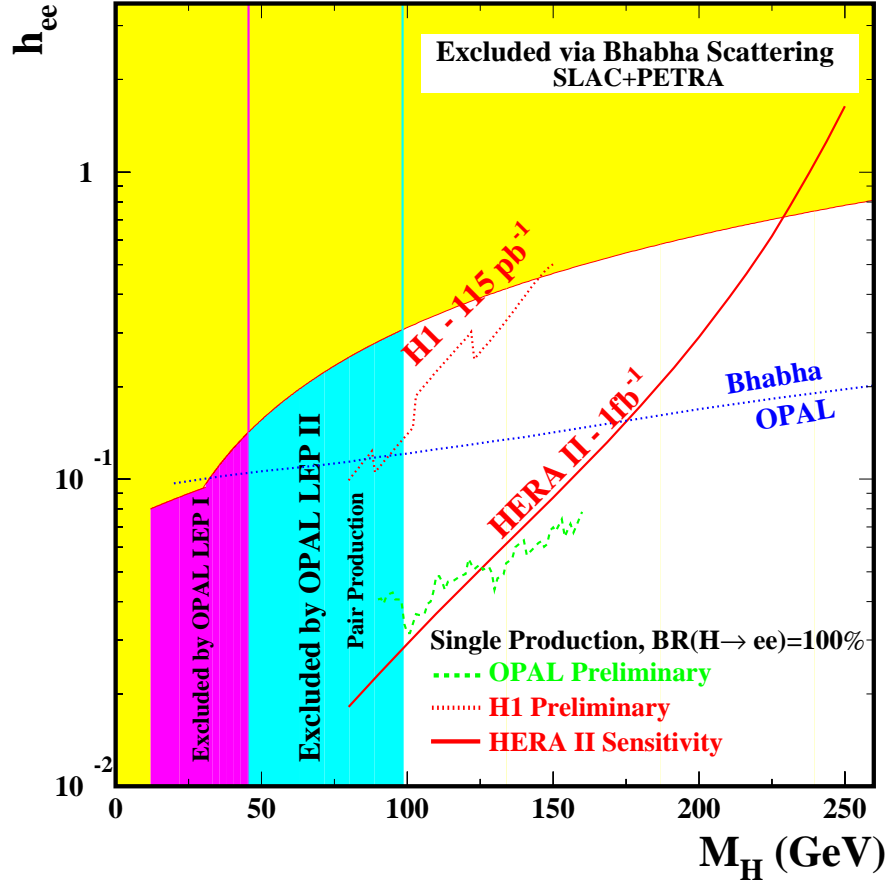


Figure 21: Existing direct and indirect constraints on doubly charged Higgs bosons in the coupling  $h_{ee}$  *vs.* mass  $M_\Delta$  plane. Recent collider results from OPAL searches [170, 172] at LEP<sub>II</sub> and from a direct search by H1 [173] at HERA<sub>I</sub> are shown together with estimated prospects for HERA<sub>II</sub>.

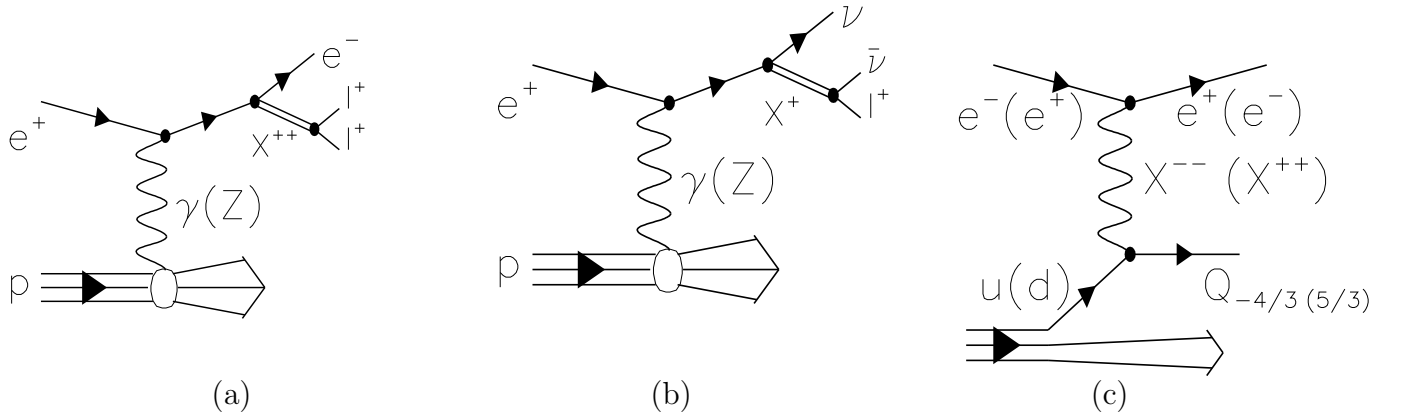


Figure 22: Typical diagrams for bilepton production at lepton-hadron colliders. a) single production of a doubly charged  $X^{++}$ ; b) single production of singly charged  $X^+$ ; c)  $t$ -channel exchange of a  $X^{--}$  ( $X^{++}$ ) bilepton in  $e^-p$  ( $e^+p$ ) leading to the creation of an exotic quark of electric charge  $-4/3$  ( $+5/3$ ).

## 7 Excited States of Fermions

The wide spectrum of “elementary constituents of matter”, i.e. the repetition of lepton and quark multiplets over three generations, leads one to speculate that they may not be the ultimate elementary particles but rather composite objects consisting of more fundamental entities. In this hypothesis, it is possible that excited states of fermions exist, at a mass scale comparable to the dynamics of the new “binding force”. They may be produced at energy-frontier colliders and would decay back “radiatively” into an ordinary fermion and a gauge boson (photon, W, Z or gluon). (Figs. 23, 24, 25)

The magnetic transition between the ordinary and excited fermions was formulated in the literature [185, 186, 187] in the following Lagrangian:

$$\mathcal{L}_{f^*f} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left[ g f \frac{\vec{\tau}}{2} \vec{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a \right] f_L + h.c.,$$

where  $\vec{W}_{\mu\nu}$ ,  $B_{\mu\nu}$  and  $G_{\mu\nu}^a$  are the field-strength tensors of the SU(2), U(1) and SU(3) gauge fields,  $\vec{\tau}$ ,  $Y$  and  $\lambda^a$  are the corresponding gauge-group generators, and  $g, g'$  and  $g_s$  are the gauge coupling constants, respectively.  $\Lambda$  is the compositeness scale and  $f, f'$  and  $f_s$  are weight parameters associated with the three gauge groups that are determined by the unknown composite dynamics.

Once produced, excited fermions  $f^*$  can decay back to the ground state by radiating a boson. For colour-neutral  $f^*$ , in the limiting case  $f = -f'$  ( $f = f'$ ), the coupling  $\gamma ee^*$  ( $\gamma \nu \nu^*$ ) vanishes and the decay must involve a  $Z$  or  $W$  boson. For excited quarks, the decay  $q \rightarrow qg$  will generally dominate if  $|f_s| \simeq |f| \simeq |f'|$ .

In  $e^+e^-$  collisions, the dominant contribution to the pair production of charged excited fermions is  $s$ -channel  $\gamma$  and  $Z$  exchange in reactions  $e^+e^- \rightarrow l^* \bar{l}^*$ ;  $\nu^* \bar{\nu}^*$ . In the case of excited neutrinos, only the

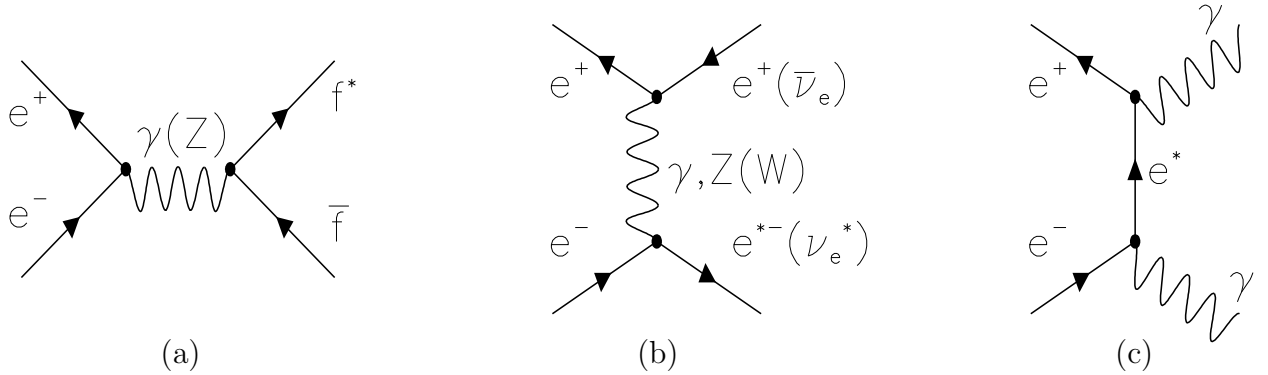


Figure 23: a) single  $f^*$  production from  $s$ -channel  $\gamma, Z$  at LEP; b) single  $e^*(\nu^*)$  production from  $t$ -channel process at LEP; c) virtual  $e^*$  exchange in  $e^+e^- \rightarrow \gamma\gamma$ .

$Z$  exchange contributes. Single production, described by the above Lagrangian, also proceeds through  $s$ -channel  $\gamma$  and  $Z$  exchange in reactions  $e^+e^- \rightarrow l^* \bar{l}^*$ ;  $\nu \nu^*$  (see Fig. 23a). For single production of  $e^*$  ( $\nu^*$ ), important additional contributions come from  $t$ -channel  $\gamma$  and  $Z$  ( $W$ ) exchange (Fig. 23b). Furthermore,  $t$ -channel exchange of a virtual  $e^*$  will give additional contribution to  $e^+e^- \rightarrow \gamma\gamma$  events, allowing LEP2 data to constrain the  $e^*$  mass domain above its centre-of-mass energy (Fig. 23c).

At HERA, excited fermions could be produced via  $t$ -channel exchange of gauge bosons as shown in Figs. 24, 25. The  $e^*$  production has a significant contribution from (quasi-)elastic production,  $ep \rightarrow$

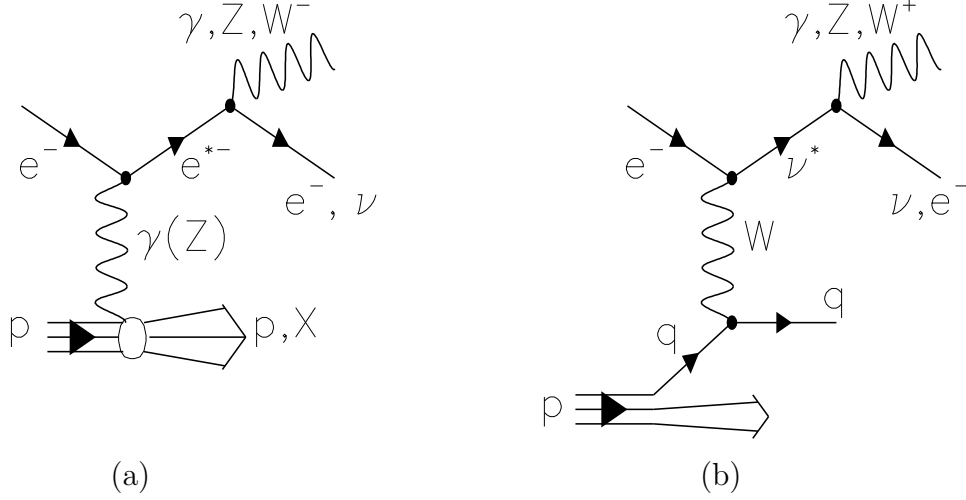


Figure 24: a)  $e^*$  production and decay at HERA; b)  $\nu^*$  production and decay at HERA.

$e^*p(e^*N)$ . The  $\nu^*$  production is a charged current reaction, resulting in much larger production cross-section for  $e^-p$  collisions compared to  $e^+p$ .

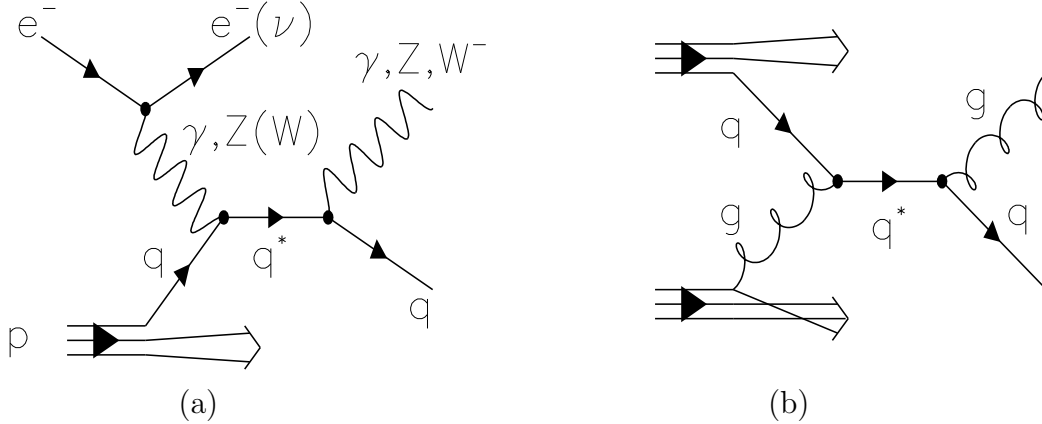


Figure 25: a)  $q^*$  production and decay at HERA; b)  $q^*$  production at Tevatron.

The Tevatron has a large discovery potential for excited quarks, provided they have considerable SU(3) coupling strength ( $f_s$ ), such that production via quark-gluon fusion (see Fig. 25) becomes significant. The signal would be an enhancement in the dijet invariant-mass distribution.

Usually experimental constraints are derived by assuming certain relations between  $f$ ,  $f'$  and  $f_s$ , by which the decay branching ratios of the excited fermions are fixed and limits are set on the single quantity  $f/\Lambda$ .

The limits on  $\nu^*$  from H1 [188] and L3 [189] are shown in Fig. 26. Corresponding results from ZEUS can be found in Ref. [190]. The  $f = +f'$  case has a vanishing branching ratio for the experimentally clean decay mode  $\nu^* \rightarrow \nu\gamma$ , thus giving worse limits. The different sensitivities between  $e^-p$  and  $e^+p$

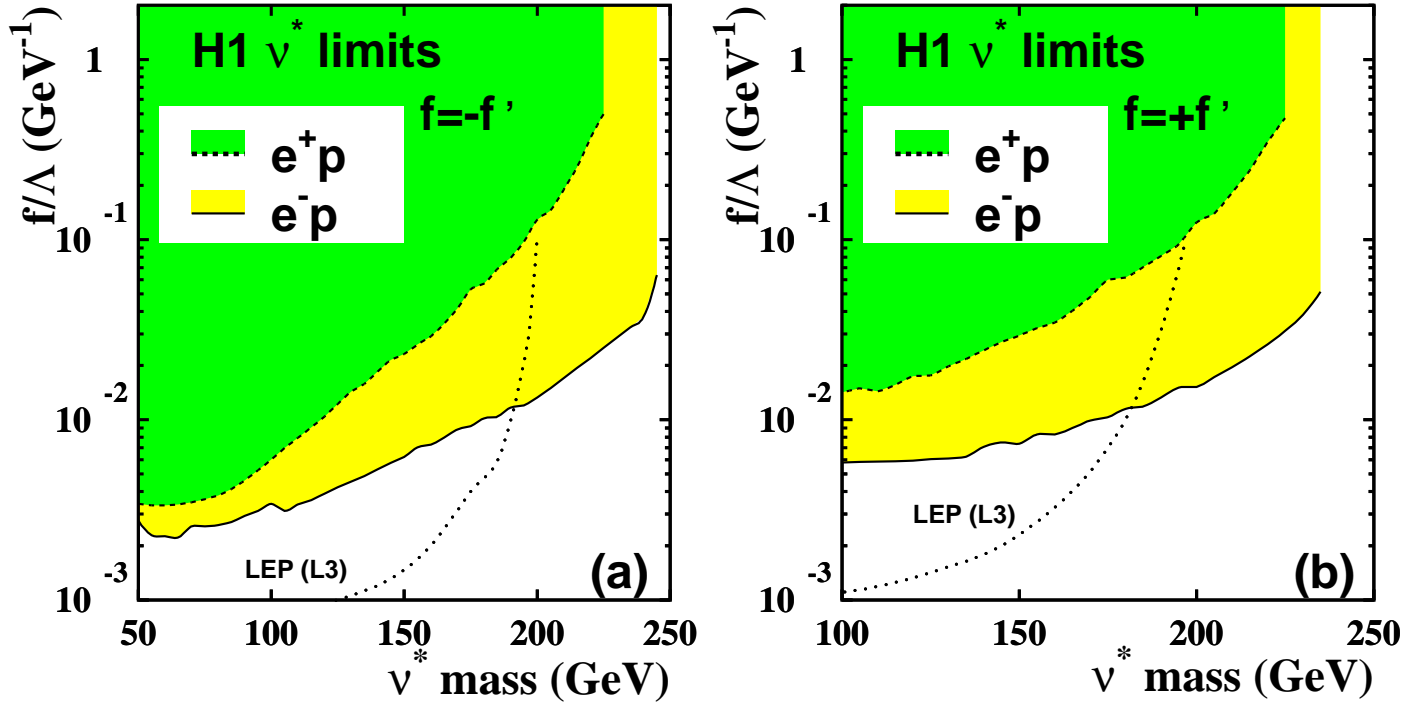


Figure 26: a) Constraints on excited neutrinos for  $f = -f'$ . b) Constraints on excited neutrinos for  $f = +f'$ .

data are evident. It can be seen that HERA offers a higher sensitivity than LEP for  $\nu^*$  masses above  $\simeq 200$  GeV.

The latest limits on  $e^*$  from HERA [191] and LEP [192] are compared in Fig. 27a. Due to the indirect sensitivity of LEP to  $e^*$  in the  $\gamma\gamma$  final state, majority of the region excluded by HERA at high mass is also excluded by LEP. Nevertheless, the expected ten-fold luminosity increase at HERA $_{II}$  will allow to cover an unexplored domain for  $e^*$  masses up to about 270 GeV. In Fig. 27b, limits on  $f$  from H1 [193] and CDF [194] are shown for  $q^*$  under the assumption  $f = +f'$  and  $\Lambda = M(q^*)$ , and for different values of  $f_s$ . It can be seen that HERA and the Tevatron have complementary sensitivities; as long as  $f_s$  is not very small, Tevatron sensitivity reaches to very high  $q^*$  masses (up to 760 GeV for  $f = f' = f_s = 1$ ), while HERA has a better sensitivity when  $f_s$  is small or vanishing, i.e. excited quarks are produced and decay predominantly with electroweak couplings.

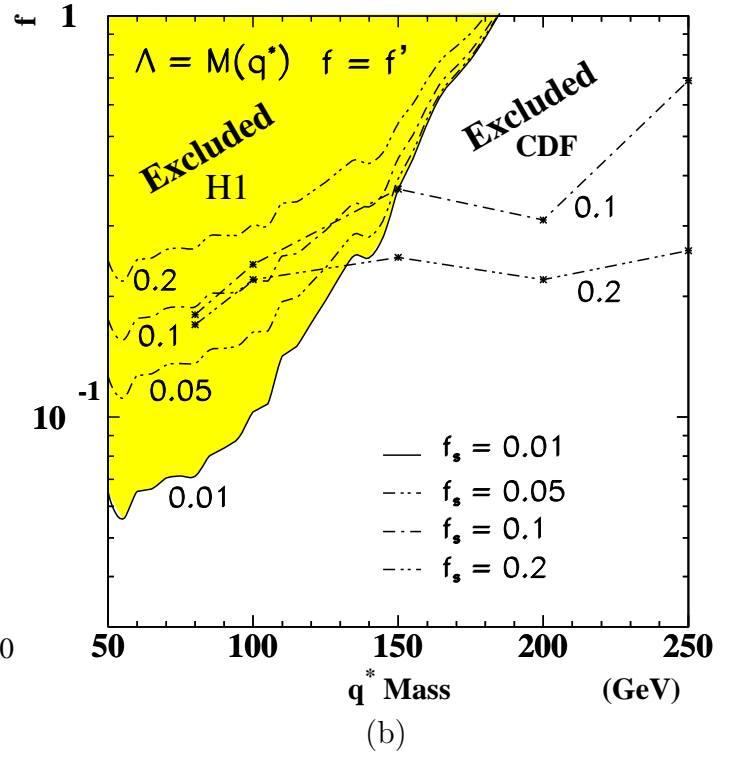
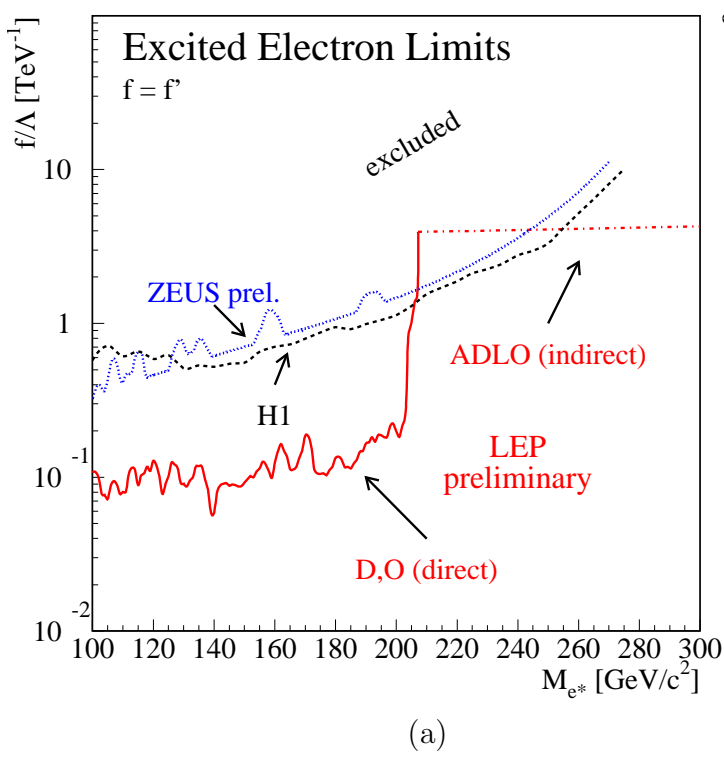


Figure 27: a) Constraints on excited electrons from HERA and LEP. b) Constraints on excited quarks from H1 and CDF.



## 8 Contact Interactions

Effects from very heavy particles  $X$ , with masses  $M_X$  much larger than the centre-of-mass energies  $\sqrt{s}$  available at a given collider, could still be detected in experiments through virtual exchange. For sufficiently heavy  $X$  particles, the propagators in the  $s$ -,  $t$ - or  $u$ -channel exchange diagram “contract” to an effective point-like four-fermion contact interaction (CI), analogous to Fermi’s proposal for a four-fermion interaction to explain  $\beta$ -decay, which subsequently was understood to be mediated by the heavy  $W$  particle in the true underlying theory. The transition from a tree-level exchange to a contact interaction is illustrated in Fig. 28. The concept of contact interaction finds an obvious application in

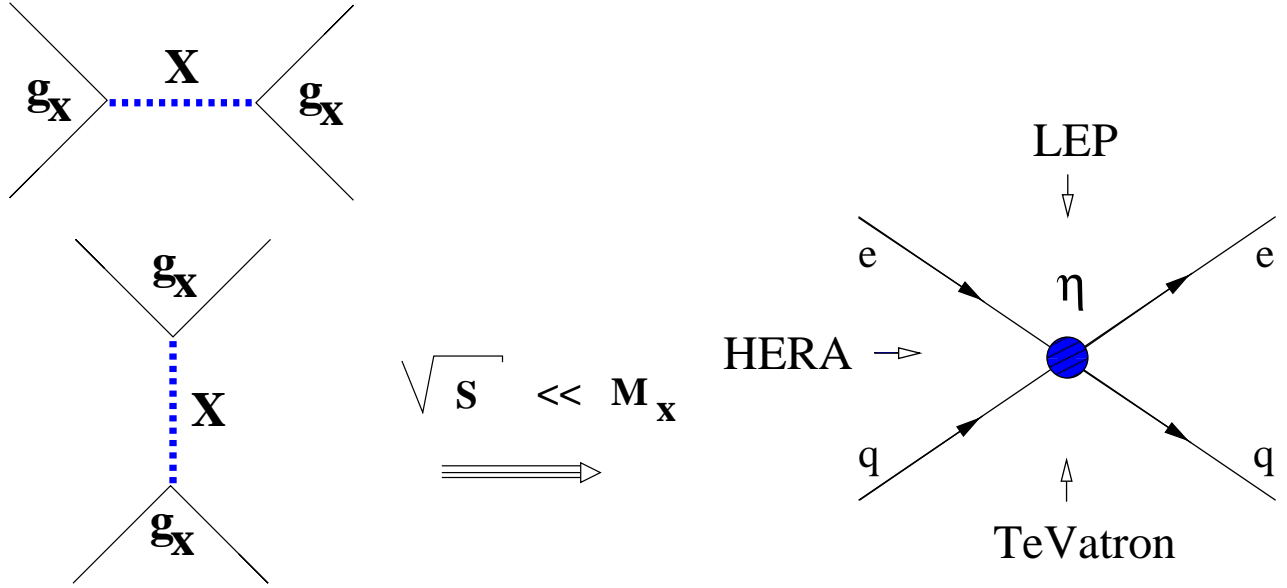


Figure 28: Schematic representation of the transition from a virtual exchange to a contact interaction. The tree-level exchanges through couplings  $g_X$  of a heavy  $X$  particle with mass  $M_X$  from some underlying (renormalizable) theory “contract” to an point-like effective four-fermion (non-renormalizable) contact interaction with couplings  $\eta \propto g_X^2/M_X^2$ . The complementarity through crossed diagrams for probing similar contact  $eeqq$  interactions at  $ep$  (HERA),  $e^+e^-$  (LEP) and  $p\bar{p}$  (Tevatron) colliders is manifest.

the search for a compositeness of ordinary leptons and quarks but is in essence much more general and is applicable to inclusive searches for various kinds of new virtual phenomena. Yet, the searches at  $ep$  and  $p\bar{p}$  colliders have been essentially restricted to neutral current (NC)-like processes in which the new particle field associated to large mass scales interferes with the ordinary  $\gamma$  and  $Z^0$  fields of the Standard Model.

The effect in NC processes of new physics at scales  $M_X \gg \sqrt{s}$  can be described [195, 196, 197] by adding a four-fermion term  $\mathcal{L}_{CI}^{NC}$  to the Standard Model interaction  $\mathcal{L}_{SM}^{NC}$ . The  $\mathcal{L}_{CI}^{NC}$  term itself can in general be decomposed into three different products of fermion bilinears containing scalar-scalar, vector-vector and tensor-tensor Lorentz-invariant structures. General expressions for these can be found in Ref. [197] where it is otherwise argued on a model-dependent basis that scalar-scalar and tensor-tensor terms are more severely constrained. Pragmatically, experimental analyses at colliders have considered the effect of vector-vector terms.

The effective Lagrangian for  $eeqq$  vector contact interactions can be written as [197]:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_q \{ \eta_{LL}^q (\bar{e}_L \gamma_\mu e_L) (\bar{q}_L \gamma^\mu q_L) + \eta_{LR}^q (\bar{e}_L \gamma_\mu e_L) (\bar{q}_R \gamma^\mu q_R) \\ + \eta_{RL}^q (\bar{e}_R \gamma_\mu e_R) (\bar{q}_L \gamma^\mu q_L) + \eta_{RR}^q (\bar{e}_R \gamma_\mu e_R) (\bar{q}_R \gamma^\mu q_R) \}$$

where the subscripts  $L$  and  $R$  denote the left- and right-handed helicity projections of the fermion fields. The values of each  $\eta_{ij}$  parameter depend on the chiral structure and dynamics of the new interaction. To quantify the experimental sensitivity, it is conventionally assumed that each  $\eta$  takes the values  $\epsilon g^2/\Lambda^2$ , where  $\Lambda$  is the mass scale of the new interaction. It is moreover conventional to assume a ‘strong’ value of  $g^2 = 4\pi$ , as was originally motivated in compositeness models. The constant  $\epsilon$  is either  $+1$ ,  $-1$  or  $0$  for each chirality combination, which defines the “model” of the new interaction. An  $\epsilon = +1$  or  $\epsilon = -1$  correspond to different signs of interference with respect to the Standard Model. The chirality structure of the CI model can be adjusted to avoid the severe constraints [198, 199] coming in particular from atomic-parity violation (APV) [94, 200, 201]. These are cancelled in particular if  $\eta_{LL}^q + \eta_{LR}^q - \eta_{RL}^q - \eta_{RR}^q = 0$  is satisfied for the quarks  $q$ , as realized for instance in the so-called  $VV$ ,  $AA$  and  $VA$  compositeness models with the mixtures  $VV = LL + LR + RL + RR$ ,  $VA = LL - LR + RL - RR$ , and  $AA = LL - LR - RL + RR$ . Isospin invariance is generally assumed in the analysis, which imposes  $\eta_{RL}^u = \eta_{RL}^d$  for all  $u$ -type and  $d$ -type quarks. The  $SU(2)$ -conserving CI scenarios with  $\eta_{LL}^u \neq \eta_{LL}^d$  would also induce  $e\nu qq'$  CI signals.

Examples of diagrams for  $eeqq$  contact interactions at each of the three existing types of high-energy colliders are shown in Fig. 29 with emphasis on the different initial- and final-state particles. In addition, four-quark (four-lepton) interactions can be probed at Tevatron (LEP). At HERA, the  $eeqq$  contact interaction (CI) would modify the NC DIS cross-sections at high  $Q^2$ . The pure-CI term would increase the cross-section at the highest  $Q^2$ , while the SM-CI interference could act either constructively or destructively in the intermediate  $Q^2$  region. Figure 30 shows preliminary  $e^-p$  and  $e^+p$  cross-sections measured by H1 as a ratio to the SM prediction [202]. Since no significant deviation is found, fits to CI models were made to obtain 95% CL exclusion limits on  $\Lambda$  for both  $\epsilon = 1$  ( $\Lambda^+$ ) and  $\epsilon = -1$  ( $\Lambda^-$ ) cases. Similarly Fig. 31 shows the  $Q^2$  distribution of NC DIS events from ZEUS, again as a ratio to SM prediction [203]. At the Tevatron, searches for  $llqq$  CI are made in Drell-Yan dilepton production. The presence of CI would alter the cross-sections at large masses. Both CDF [204] and DØ [205] have obtained limits for  $eeqq$  terms from di-electron data. CDF [204] also looked at di-muon data which constrained  $\mu\mu qq$  terms. At LEP2 [206, 207, 208, 209], measurements of hadronic cross-sections constrained  $eeqq$  CI terms.

Table 11 summarizes the limits from three colliders for various  $eeqq$  CI models with different chiral structures. Except for the purely chiral models (LL, LR, RL and RR), all models in the table respect the above mentioned condition imposed by APV experiments. Each row of the table corresponds to two models, depending on the overall interference sign with respect to the SM. Note that the limits from LEP were obtained under the assumption that all quark flavours participate in the CI reaction, while the HERA and Tevatron results are sensitive to first-generation quarks, which dominate the high- $x$  region of the proton structure function.

The Tevatron  $\bar{p}p$  experiments are also sensitive to  $qqqq$  CI models by comparing hadronic-jet production with the QCD predictions. Limits on  $\Lambda$  as high as 2.4 TeV have been obtained from observables such as dijet mass or angular distributions [210]. Recently CDF has also looked for  $qq'e\nu$ -type CI effects in the high-mass  $e\nu$  final state and derived a lower limit of 2.81 TeV on  $\Lambda$  [211].

The results above could also be interpreted in terms of “radius” of the quark, with the classical form-factor approximation. For example, the high- $Q^2$  NC DIS cross-section will decrease by a factor  $(1 - R_e^2/6Q^2)^2(1 - R_q^2/6Q^2)^2$  under the assumption of non-zero root-mean-square electroweak radii of electron and quark, respectively. Assuming a point-like electron ( $R_e=0$ ), limits on  $R_q$  of  $0.82 \cdot 10^{-16}\text{cm}$  and  $0.73 \cdot 10^{-16}\text{cm}$  have been obtained from H1 [202] and ZEUS [203] data, respectively. Figure 32 shows an example from ZEUS. CDF [204] gives a limit of  $0.79 \cdot 10^{-16}\text{cm}$  from the Drell-Yan results<sup>5</sup> and L3 [208] gives  $0.42 \cdot 10^{-16}\text{cm}$ , but the latter assumes that all produced flavours are composite.

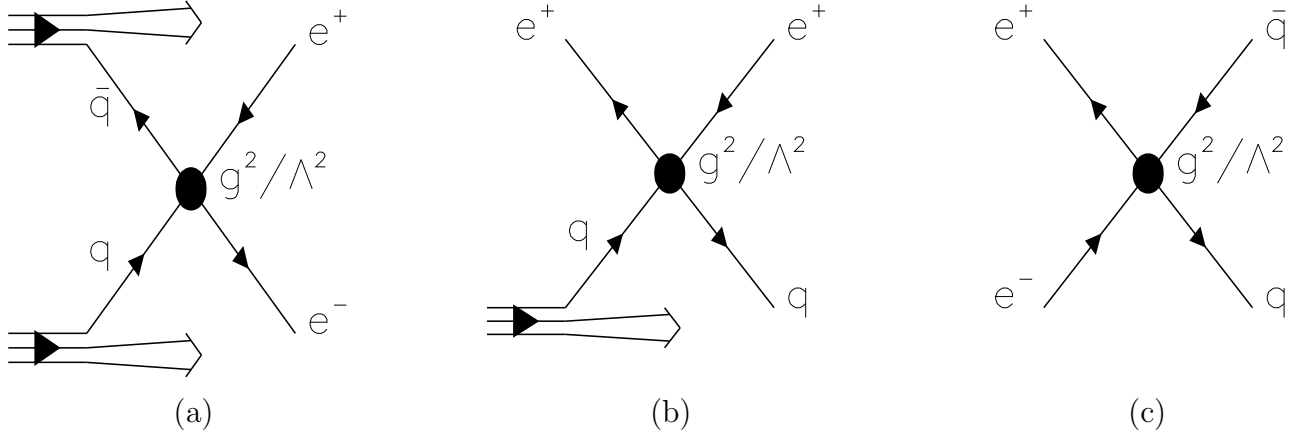


Figure 29: Probing  $eeqq$  contact interactions in a)  $p\bar{p}$ , b)  $ep$  and c)  $e^+e^-$  colliders.

The leptoquarks described in section 2, when much heavier than the centre-of-mass energy of the collider, can influence the SM processes via virtual effects with  $s$ -,  $u$ - (for HERA) or  $t$ -channel exchange (at LEP and Tevatron). Their effect at the low-energy limit can be expressed as a CI model in which  $g/\Lambda$  is replaced with  $\lambda/M$ , the ratio between the Yukawa coupling and the leptoquark mass, and the coefficients  $\epsilon_{ij}^q$  take particular constant values depending on the leptoquark species, as in Table 12. The table summarizes the limits from HERA [202, 203] and LEP2 [206, 208, 212]. Also listed in Table 12 are low energy constraints derived in Ref. [13] from precision measurements of APV and of lepton universality in  $\pi \rightarrow l\nu_l$  decays. The constraints from low energy measurements alone are seen to exclude a domain already beyond the reach of actual HERA data for leptoquarks in the CI limit ( $M_{LQ} \gg \sqrt{s_{ep}}$ ). As was shown in Ref. [213], this will remain so at HERA<sub>II</sub> even when considering integrated luminosities  $\mathcal{L}$  approaching  $1 \text{ fb}^{-1}$  in a single experiment, given that the mass reach only improves in powers of  $\mathcal{L}^{1/4}$ . Combining [214, 215] all existing data from colliders and low energy experiments leads to so-called “global fit” constraints shown for comparison in Table 12 from the analysis of Ref. [214]. As was shown in Ref. [213], only the full integrated luminosity expected in the lifetime of Tevatron<sub>II</sub> will allow a single collider experiment to start to compete in sensitivity with these existing bounds.

<sup>5</sup>derived from the quoted limit of  $0.56 \cdot 10^{-16}\text{cm}$  which assumes  $R_e=R_q$

95% CL limit [TeV]		ZEUS		H1		DØ		CDF		ALEPH		L3		OPAL	
Coupling structure															
Model	$[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$	$\Lambda^-$	$\Lambda^+$
LL	[+1, 0, 0, 0]			2.3	2.8	4.2	3.3	3.7	2.5	6.2	5.4	2.8	4.2	3.1	5.5
LR	[0, +1, 0, 0]			1.8	3.2	3.6	3.4	3.3	2.8	3.3	3.0	3.5	3.3	4.4	3.8
RL	[0, 0, +1, 0]			1.9	3.2	3.7	3.3	3.2	2.9	4.0	2.4	4.6	2.5	6.4	2.7
RR	[0, 0, 0, +1]			2.3	2.8	4.0	3.3	3.6	2.6	4.4	3.9	3.8	3.1	4.9	3.5
VV	[+1, +1, +1, +1]	7.0	6.5	5.4	5.1	6.1	4.9	5.2	3.5	7.1	6.4	5.5	4.2	7.2	4.7
AA	[+1, -1, -1, +1]	5.3	4.6	3.9	2.5	5.5	4.7	4.8	3.8	7.9	7.2	3.8	6.1	4.2	8.1
VA	[+1, -1, +1, -1]	3.4	3.3	2.9	2.9										
LL-LR	[+1, -1, 0, 0]	4.0	2.7			4.5	3.9								
LL+RL	[+1, 0, +1, 0]	4.7	4.7												
LL+RR	[+1, 0, 0, +1]	4.3	4.2	3.7	3.8	5.1	4.2			7.4	6.7	3.7	4.4	4.4	5.4
LR+RL	[0, +1, +1, 0]	5.6	5.6	4.1	4.3	4.4	3.9			4.5	2.9	5.2	3.1	7.1	3.4
LR+RR	[0, +1, 0, +1]	4.8	4.8												
RL-RR	[0, 0, +1, -1]	2.6	3.9			4.3	4.0								

Table 11: Relations between couplings  $[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$  for the compositeness models and the 95% CL lower limits on the compositeness scale,  $\Lambda$ , resulting from HERA, Tevatron and LEP2 experiments. Each row of the table represents two  $eeqq$  CI scenarios corresponding to the coupling structure defined in the leftmost column ( $\Lambda^+$ ) and another with all  $\epsilon$ 's negated ( $\Lambda^-$ ). The same coupling structure applies to  $d$  and  $u$  quarks.

95% CL limit $M_{LQ}/\lambda_{LQ}$ [TeV]								
CI Model		Collider Experiments					Low Energy	Global Fits
LQ type	Coupling Structure	ZEUS	H1	ALEPH	L3	OPAL	(APV and $\pi \rightarrow e\nu$ )	
$S_\circ^L$	$\epsilon_{LL}^u = +\frac{1}{2}$	0.75	0.72	0.64	1.24	0.64	3.5	3.7
$S_\circ^R$	$\epsilon_{RR}^u = +\frac{1}{2}$	0.69	0.67		0.96		2.8	3.9
$\tilde{S}_\circ^R$	$\epsilon_{LL}^d = +\frac{1}{2}$	0.31	0.33	0.22	0.26	0.59	3.0	3.6
$S_{1/2}^L$	$\epsilon_{LR}^u = -\frac{1}{2}$	0.91	0.87	0.06	0.18	0.46	2.8	3.5
$S_{1/2}^R$	$\epsilon_{RL}^d = \epsilon_{RL}^u = -\frac{1}{2}$	0.69	0.37		0.35	0.63	2.1	2.1
$\tilde{S}_{1/2}^L$	$\epsilon_{LR}^d = -\frac{1}{2}$	0.50	0.43			0.37	3.0	3.8
$S_1^L$	$\epsilon_{LL}^d = +1, \epsilon_{LL}^u = +\frac{1}{2}$	0.55	0.48	0.77	0.64	0.93	2.5	2.4
$V_\circ^L$	$\epsilon_{LL}^d = -1$	0.69	0.77	1.09	1.79		4.3	8.1
$V_\circ^R$	$\epsilon_{RR}^d = -1$	0.58	0.64	0.38	0.41	0.45	2.2	2.3
$\tilde{V}_\circ^R$	$\epsilon_{RR}^u = -1$	1.03	1.00	0.89	0.89	1.10	2.0	1.9
$V_{1/2}^L$	$\epsilon_{LR}^d = +1$	0.49	0.42	0.41	0.61	0.66	5.4	2.1
$V_{1/2}^R$	$\epsilon_{RL}^d = \epsilon_{RL}^u = +1$	1.15	0.94	0.48	0.54	0.60	2.2	7.5
$\tilde{V}_{1/2}^L$	$\epsilon_{LR}^u = +1$	1.26	1.02	0.29	0.45	0.55	2.0	2.1
$V_1^L$	$\epsilon_{LL}^d = -1, \epsilon_{LL}^u = -2$	1.42	1.38	1.50	1.21	1.53	6.6	7.3

Table 12: Lower limits (95% CL) on the ratio  $M_{LQ}/\lambda_{LQ}$  of the leptoquark mass  $M_{LQ}$  to the Yukawa coupling  $\lambda_{LQ}$  for various contact-interaction models. The models are defined by the coefficients  $\epsilon_{ij}^q$  and correspond to the interactions of scalar leptoquarks  $S$  (upper table part) and vector leptoquarks  $V$  (lower table part) of different types in the limit  $M_{LQ} \gg \sqrt{s}$ . Results are summarized for the CI analysis of HERA [202, 203] and LEP2 [206, 208, 212] data. Low energy constraints [13] derived from Atomic Parity Violation (APV) measurements and precision tests of lepton universality in  $\pi \rightarrow l\nu_l$  decays are also summarized. Results from “global fits” [214, 215] (see text) are shown for comparison.

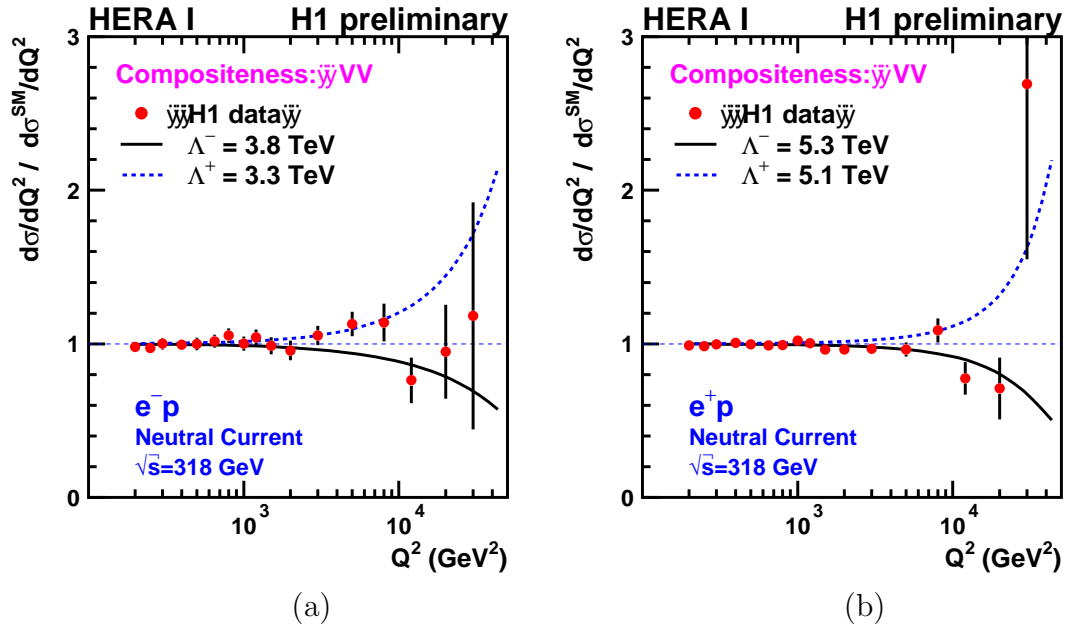


Figure 30: Ratio of a)  $e^-p$  and b)  $e^+p$  NC DIS cross-sections, measured by H1, divided by the SM prediction. The curves are VV CI models corresponding to 95% CL exclusion obtained from each data set.

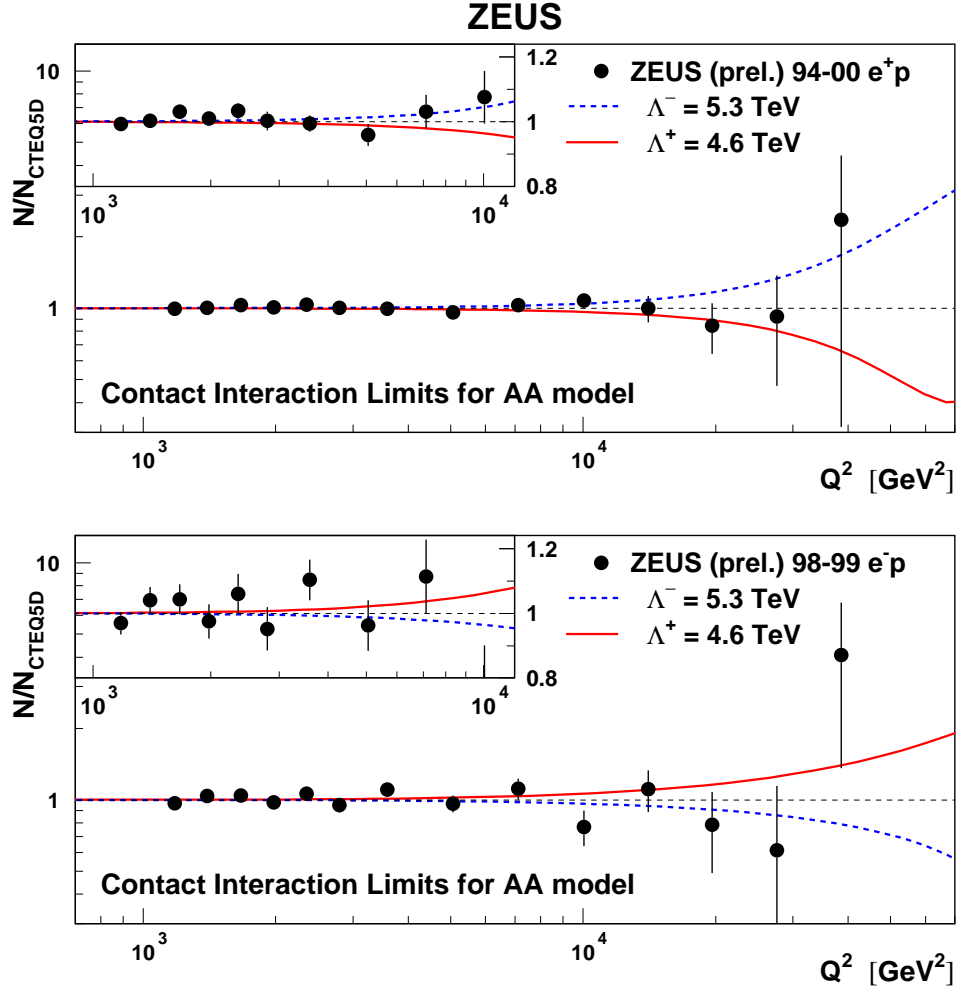


Figure 31: Ratio of  $e^+p$  (*top*) and  $e^-p$  (*bottom*) NC DIS events observed by ZEUS, divided by the SM prediction. The curves are AA CI models corresponding to 95% CL exclusion obtained from the combined data set.

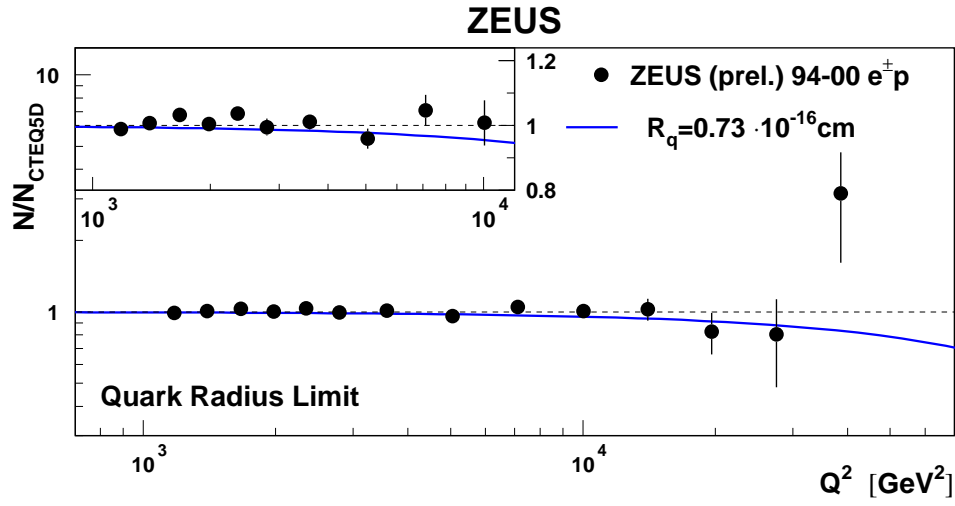


Figure 32: Ratio of  $e^\pm p$  NC DIS events observed by ZEUS, divided by the SM prediction. The curve corresponds to the quark form factor at which the limit is set.



## 9 Large Compactified Extra Dimensions

It has been realized recently that the problem of the hierarchy between the electroweak scale and the Planck scale, two seemingly fundamental scales in Nature, could be solved in theories with extra dimensions. Viable scenarios have been constructed in  $(4+n)$ -dimensional string-inspired theories such as the Arkani-Hamed, Dimopoulos and Dvali (ADD) model [216] with  $n \geq 2$  “large” compactified extra dimensions, or the Randall–Sundrum model [217] with  $n = 1$  “small” and (so-called) “warped” extra spatial dimension. In such quantum-gravity models, the gravitational force is expected to become comparable to the gauge forces close to the weak scale, eventually leading to (model dependent) effects in the TeV range observable at high energy colliders [218, 219, 220, 221, 222, 223]. The phenomenology and results discussed below are based on the ADD scenario.

In the ADD scenario, a gravitational “string” scale,  $M_s$ , in  $(4+n)$  dimensions is introduced close to the weak scale. It is related to the usual Planck scale,  $M_p \sim 10^{19}$  GeV (which is no longer fundamental but now rather merely the scale of effective four-dimensional gravity), via a relation  $M_p^2 = R^n M_s^{2+n}$ , where  $R$  is a characteristic (large) size of the  $n$  compactified extra dimensions. The graviton is allowed to propagate in these extra dimensions. Their finite size  $R$  implies that the graviton will appear in our familiar 4-dimensional universe as a “tower” of massive Kaluza-Klein excitation states. The effects from virtual graviton exchange are expected to depend only weakly on the number of extra dimensions, while in contrast direct graviton emission is expected to be suppressed by a factor  $(M_s)^{n-2}$  [218, 219]. The virtual exchange of Kaluza-Klein towers between Standard Model particles leads to an effective contact interaction with a coupling coefficient  $\eta_G = \lambda/M_s^4$  [219]. Of the spin-0, 1 and 2 states of the Kaluza-Klein towers, only the spin-2 gravitons interact in the ADD scenario with the Standard Model fields of our familiar universe [218, 222].

The contributions of virtual graviton exchange to deep inelastic scattering in  $ep$  collisions have been derived in Ref. [224] by applying crossing relations to the cross-sections given in Ref. [219] for  $e^+e^-$  collisions. At the parton level, the differential cross-sections for the basic processes of elastic  $e^+q \rightarrow e^+q$  and  $e^+g \rightarrow e^+g$  scattering can be written as

$$\begin{aligned} \frac{d\sigma(e^+q \rightarrow e^+q)}{dt} &= \frac{d\sigma^{SM}}{dt} + \frac{d\sigma^G}{dt} + \frac{d\sigma^{\gamma G}}{dt} + \frac{d\sigma^{ZG}}{dt} , \\ \frac{d\sigma^G}{dt} &= \frac{\pi \lambda^2}{32 M_s^8} \frac{1}{s^2} \{ 32 u^4 + 64 u^3 t + 42 u^2 t^2 + 10 u t^3 + t^4 \} , \\ \frac{d\sigma^{\gamma G}}{dt} &= -\frac{\pi \lambda}{2 M_s^4} \frac{\alpha e_q}{s^2} \frac{(2u+t)^3}{t} , \\ \frac{d\sigma^{ZG}}{dt} &= \frac{\pi \lambda}{2 M_s^4} \frac{\alpha}{s^2 \sin^2 2\theta_W} \left\{ v_e v_q \frac{(2u+t)^3}{t - m_Z^2} - a_e a_q \frac{t(6u^2 + 6ut + t^2)}{t - m_Z^2} \right\} , \\ \frac{d\sigma(e^+g \rightarrow e^+g)}{dt} &= \frac{\pi \lambda^2}{2 M_s^8} \frac{u}{s^2} \{ 2 u^3 + 4 u^2 t + 3 u t^2 + t^3 \} , \end{aligned}$$

where the contributions of the Standard Model (SM), of the pure graviton (G) exchange and of  $\gamma G$  and  $ZG$  interference have been distinguished. Here  $s$ ,  $t = -Q^2$  and  $u$  are the Mandelstam variables,  $e_q$  is the quark charge and  $v_f$  and  $a_f$  are the vector and axial-vector couplings of the fermions to the  $Z$ . The corresponding cross-sections for  $e^+\bar{q}$  scattering are obtained by replacing  $v_q \rightarrow -v_q$  and  $e_q \rightarrow -e_q$  in the

expressions above. For  $e^-q$  scattering, the interference of the graviton exchange with  $\gamma$  and  $Z$  exchange behaves oppositely to that in  $e^+q$  scattering. Integral expressions for the inclusive  $e^+p$  cross-section obtained by integrating over parton distributions in the proton are given in Ref. [224]. The gravitational effects arising from the gluon contribution are expected to be small,  $\mathcal{O}(1\%)$ , compared to those coming from quarks and antiquarks.

Results from HERA experiments on the search for virtual graviton exchange in theories with large extra dimensions are given in Figs. 33 [202] and 34 [203]. The high- $Q^2$  NC DIS events are presented as a ratio to the SM prediction, together with the effect of Kaluza-Klein graviton exchange at a mass scale excluded at 95% CL. Here the coupling  $\lambda$ , which depends on the full theory and is expected to be of order unity, has been fixed by convention to  $\lambda = \pm 1$ . A combined analysis of the  $e^-p$  and  $e^+p$  data yields very similar lower limits on  $M_S$  for both  $\lambda = +1$  and  $\lambda = -1$  of about 0.8 TeV.

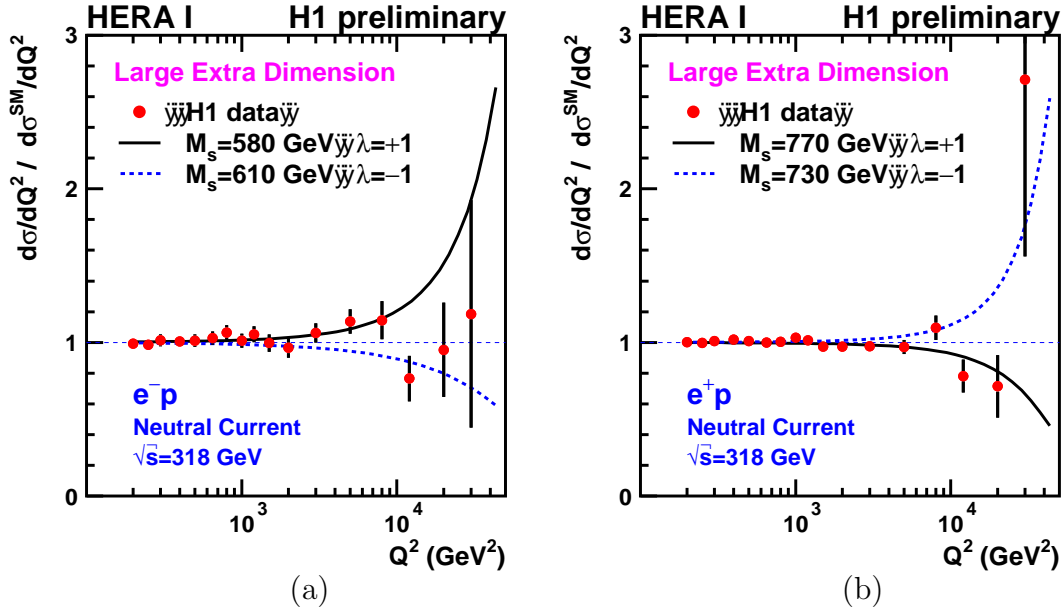


Figure 33: Comparison of the deep inelastic neutral current differential a)  $e^-p$  and b)  $e^+p$  cross-section measured by H1 with expectations from the Standard Model; expected effects from the exchange of Kaluza-Klein towers of gravitons for values of the string scales derived as the 95% CL lower limit are also shown. A combined analysis of the  $e^-p$  and  $e^+p$  data yields a lower limit on  $M_S$  of 0.83 TeV for  $\lambda = +1$  and 0.79 TeV for  $\lambda = -1$ .

Searches for virtual effects from theories with large extra dimensions have also been reported from Tevatron [225] and LEP experiments [226]. The  $D\bar{\theta}$  experiment at the Tevatron considered di-electron and di-photon invariant mass and angular distributions and compared these to Standard Model expectation. The analysis made use of the entire sample of data collected by  $D\bar{\theta}$  at Tevatron<sub>I</sub>, which corresponds to an integrated luminosity of  $\approx 130 \text{ pb}^{-1}$ . No deviation from expectation was observed, and a lower limit on the mass scale  $M_S$  of 1.2 TeV (95% CL) was obtained<sup>6</sup>. The L3 and OPAL exper-

<sup>6</sup>The results given here are expressed in the formalism of Giudice, Rattazzi and Wells [219]. Collider results are also often discussed in the formalisms of Hewett [218] or that of Han, Lykken and Zhang [227] where a different definition of the coupling coefficient  $\eta_G$  is used.

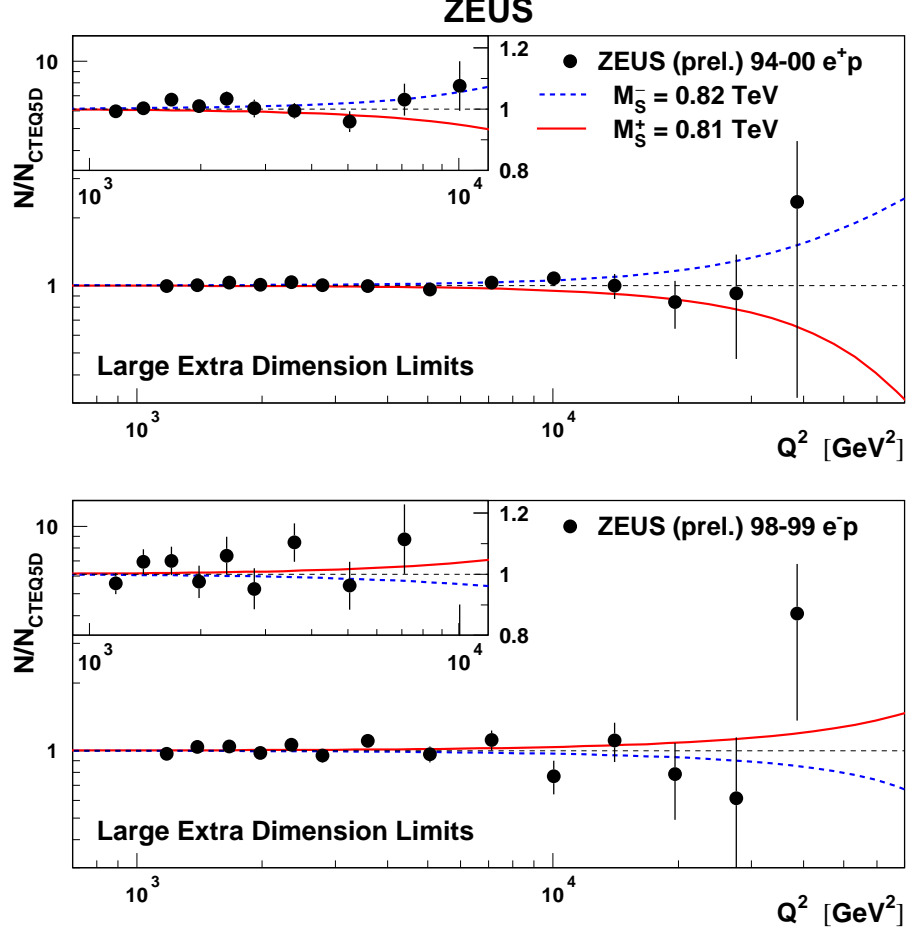


Figure 34: Comparison of high- $Q^2$  deep inelastic neutral current events measured by ZEUS with expectations from the Standard Model; curves show the expected effects from the exchange of Kaluza-Klein towers of gravitons for values of the string scales derived as the 95% CL lower limit from combined  $e^+p$  and  $e^-p$  data.

iments at LEP have searched for effects from virtual exchange of gravitons in fermion-pair production  $e^+e^- \rightarrow f\bar{f}$  in analyses making use of an integrated luminosity of  $\approx 180 \text{ pb}^{-1}$  collected per experiment at  $\sqrt{s} = 189 \text{ GeV}$ . The L3 analysis in addition considers boson-pair production  $e^+e^- \rightarrow \gamma\gamma, WW, ZZ$ . No deviation from Standard Model expectation was observed and the LEP<sub>II</sub> searches yielded lower limits of about 1 TeV.

## 10 Summary

In this paper we have reviewed the status of searches for physics beyond the Standard Model of electroweak and strong interactions at LEP<sub>I</sub>, LEP<sub>II</sub>, Tevatron<sub>I</sub> and HERA<sub>I</sub> colliders. We also have presented new avenues for discoveries at the (upgraded) Tevatron<sub>II</sub> and HERA<sub>II</sub> colliders.

Leptoquark colour-triplet bosons are seen to be ideally suited to searches at  $ep$  and  $\bar{p}p$  colliders. Such scalar or vector bosons are predicted in various unification theories, as a consequence of the symmetry between the leptonic and quarkonic sectors. The CDF and DØ experiments at the Tevatron collider offer the best discovery mass reach for leptoquark bosons of all three generations if they appear in the context of minimal models with interactions invariant under  $SU(3) \times SU(2) \times U(1)$  gauge groups. In a more general context where leptoquarks could have a low decay branching fraction into final states containing first- or second-generation charged leptons, a complementary sensitivity is offered by the H1 and ZEUS experiments at the HERA collider. At HERA<sub>II</sub>, leptoquarks with masses approaching 300 GeV could be discovered for Yukawa coupling values corresponding to an interaction of electromagnetic strength. We have seen that HERA also offers a sensitivity beyond existing low-energy indirect constraints if leptoquarks are allowed to mediate lepton-flavour violating transitions.

Leptoquark-like composite objects appear as bound states of fundamental “preons” in some compositeness theories. They also appear as “technipions”  $\pi_{LQ}$  in some specific Technicolour theories which address the problem of electroweak symmetry breaking via a dynamical mechanism. We have discussed stringent constraints established at the Tevatron on the technihadrons of Technicolour theories. We mentioned the possible interest of  $t$ -channel  $\pi_{LQ}$  production for HERA<sub>II</sub>.

The relatively low energy scale at which electroweak symmetry breaking occurs when compared to characteristic Grand Unification energy scales is accommodated naturally in supersymmetric (SUSY) theories. The search for the SUSY partners of ordinary particles has constituted a major theme in high energy physics over the past decades. We have discussed how the collider phenomenology depends on assumptions made for the parameters of specific SUSY models and on the chosen (a priori unknown) mechanism responsible for the breaking of the supersymmetry. A review of the best (and least model-dependent) existing lower limits on sparticle masses was presented. The most stringent constraints on gaugino-higgsinos and sleptons have been established at the LEP collider for a very wide range of parameters of either the Minimal SUSY Standard Model, Minimal Supergravity models or Gauge Mediated SUSY Breaking models. If the  $R$ -parity quantum number which distinguishes ordinary particles ( $R_p = +1$ ) from supersymmetric particles ( $R_p = -1$ ) is exactly conserved in Nature, the best opportunity for a discovery will be provided by squark and gluino searches at the Tevatron<sub>II</sub> collider. The discovery mass reach for sfermions at colliders can be considerably enlarged by single sparticle real production or virtual exchange involving  $\tilde{R}_p$  Yukawa couplings. We have discussed with some emphasis the case of the lepton-number violating couplings  $\lambda'$  which could allow for resonant squark production at HERA through lepton-quark fusion or resonant slepton production at the Tevatron through quark-antiquark fusion.

$R$ -parity violation is a possible source of flavour-changing neutral currents (FCNC) which are also predicted for instance in various models incorporating an extended Higgs sector. We have seen that HERA and Tevatron experiments have access, with large integrated luminosities, to possible FCNC processes beyond the reach of LEP<sub>II</sub> via anomalous magnetic couplings of the top to lighter up or charm quarks.

We have discussed prominent models that rely on an extension of the standard electroweak gauge

symmetries with emphasis on left-right symmetric models and on models containing triplets of lepton or quark fields. These models predict the existence of extra gauge bosons such as an extra  $W'$  which couples to right-handed quarks and of exotic Higgs particles such as a doubly charged scalar coupling to lepton pairs. We have seen that very stringent constraints are established at the Tevatron on the  $W'$  mass for a wide range of values of the model parameters which include the coupling constant  $g_R$  of the  $W'$  to right-handed fermions, the mixing angle  $\xi$  between the  $W_L$  and  $W_R$  states, and the mass(es) and nature (Dirac or Majorana) of some new right-handed neutrinos. A complementary sensitivity could be offered by the HERA<sub>II</sub> collider only for very drastic choices of the quark mass-mixing matrix in the right-handed sector and provided that very high precision can be obtained for the lepton-beam polarisation. We have argued that doubly charged Higgs bosons  $\Delta^{\pm\pm}$  could remain accessibly light even in left-right symmetric models with Majorana neutrinos and  $W'$  bosons beyond the reach of colliders. We have shown that the  $\Delta^{\pm\pm}$  would lead to striking event topologies in particular at the HERA collider.

We discussed the possibility of creating excited states of fermions via magnetic transitions from the ground state of leptons or quarks in compositeness models. Excited electrons and neutrinos could be discovered at the HERA<sub>II</sub> collider while excited quarks could be discovered at Tevatron<sub>II</sub> collider. The HERA<sub>II</sub> and Tevatron<sub>II</sub> colliders were shown to offer a comparable sensitivity via four-fermion processes to compositeness (or in general virtual exchange of very heavy particles) with characteristic mass scales in the TeV range. We have furthermore shown that inclusive measurements could be used to set stringent constraints on models with extra compactified dimensions.

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